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PROPOSED REFERENCE IRRADIANCE SPECTRA FOR SOLAR ENERGY SYSTEMS TESTING

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Abstract—In 1982, the American Society for Testing and Materials (ASTM) adopted consensus standard solar terrestrial spectra (ASTM E891-82, E892-82) to provide standard spectra for photovoltaic (PV) performance applications. These spectra have been also used for other applications such as solar energy systems, fenestration, and materials degradation. These reference spectra were recomputed and the standards revised in 1987. The International Standards Organization (ISO) and International Electrotechnical Commission (IEC) adopted these spectra into spectral standards ISO 9845-1 and IEC 60904-3. These reference spectra are current as of 2002, even though they are based upon spectral solar radiation models and information on atmospheric attenuation from the 1980s. We summarize important issues concerning the definition of atmospheric parameters, spectral range, accuracy and resolution, and documentation of the standards. We suggest substantial improvements to meet the current and future needs of the various technologies using the reference spectra. Modern terrestrial spectral radiation models and better knowledge of atmospheric physics and prevailing radiometric quantities in the natural environment are used to develop suggested revisions to update the reference spectra. These revisions extend and improve the documentation of the hemispherical ('global') tilted reference spectrum with minor modifications. They also provide a more realistic clear sky direct normal spectrum for the intended applications. The revised reference spectra would include more detailed and reliable spectral information from the UV (280 nm) to the near infrared (4000 nm). The amplitude of the proposed hemispherical tilted reference spectrum differs very little from the current standard hemispherical tilted spectrum. Conversely, the proposed direct normal reference spectrum is substantially more energetic than the current standard spectrum, and is typical of a cleaner atmosphere where solar applications can be deployed more advantageously.
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1. INTRODUCTION

Growth of the terrestrial photovoltaic (PV) manufacturing industry and associated renewable energy research and development in the 1980s resulted in the development of reference standard reporting conditions to evaluate the relative performance of various PV materials and devices. The American Society for Testing and Materials (ASTM, see http://www.astm.org) committee E44 on Solar, Geothermal, and Other Alternative Energy Sources developed standards to meet these needs. The committee developed standards for standard reporting conditions (ASTM, 1998b), calibrating reference cells and modules and evaluating the performance of cells, modules and devices (Osterwald, 1992).

Fixed reference solar spectra are an important component of standard reporting conditions for such spectrally selective devices as PV cells and modules (Emery, 1999). The committee made use of then available atmospheric spectral solar transmission models, measured data, and standard atmospheric conditions to produce two reference spectra thought to be representative of reasonable natural conditions and PV applications. These spectra (originally ASTM E891-82, for *direct normal spectral irradiance*, and E892-82, for *total hemispherical spectral irradiance on a south facing* 37° *tilted surface*) were first approved by ASTM in 1982, based on preliminary data. The spectra were then recalculated (resulting in significant changes) based upon published references (Bird *et al*., 1983; Hulstrom *et al*., 1985). These changes were approved in 1987 and re-approved in 1992 (ASTM, 1987a,b). The 1982 and 1987 spectra replaced the older E424-71 standard spectrum (approved 1971) based on much older calculations (Moon, 1940). The ASTM standards were introduced at the international level as well. The E892-87 spectrum was adopted by the International Electrotechnical Commission (IEC, 1989). Shortly after, the International Standards Organization (ISO) adopted both E891-92 and E892-92 spectra into a single standard (ISO, 1992). This means that, although the focus is here

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on the history and future of the ASTM standards, the discussions and recommendations that follow apply to the international standards as well.

In 1998 the standard spectra were moved to the jurisdiction of ASTM subcommittee G03.09 on Solar Radiometry. That committee editorially (i.e. with no changes in technical content) combined E891-92 and E892-92 into ASTM G159-98 (ASTM, 1998a) to be consistent with the ISO standard. In 1999, ASTM formally withdrew E891 and E892, replacing them with the combined G159-98 standard.

The reference spectra represent terrestrial solar spectral irradiance incident on a specific surface, under *one* set of specified atmospheric conditions. The direct normal spectrum is the direct component contributing to the total hemispherical (or 'global') radiation on a 37°-tilted surface. The primary references describing the conditions and parameters entering into the existing standards are the papers by Bird *et al.* (1983) (hereafter, BHL83), and Hulstrom *et al.* (1985) (HBR85). The same authors also published eight alternative spectra covering a range of conditions bracketing those of the standards (Bird and Hulstrom, 1983).

After more than 15 years without modification, technical issues related to the models used, environmental conditions, documentation, usability, significance, and validity of these spectra have arisen. These issues suggest updates are needed to meet the greater technical demands of industry and users in the PV, solar energy systems, materials degradation, fenestration, and other areas.

2. SOLAR GEOMETRY IN CURRENT STANDARDS

The geometric conditions selected were considered reasonable averages for flat plate PV modules deployed in the United States of America. The receiving surface is defined as an inclined plane tilted at 37° from the horizontal toward the equator, facing south (azimuth of 180°), or, in simpler words, a 37°-tilt, sun-facing surface. This tilt was selected as it represented the average latitude of the contiguous 48 United States.

The only specification with respect to the solar position is that the air mass (AM, path length through the atmosphere relative to the zenith, or overhead position) is equal to 1.5, for an observer at sea level. For such an observer and an ideal plane-parallel atmosphere, the geometrical, or *relative*, air mass is defined as the secant of the apparent zenith angle, *Z*, (angle between the zenith and the sun, obtained as the true astronomical zenith angle minus refraction) equivalent to the cosecant of the elevation angle. Thus for AM = 1.5, the zenith angle for the sun is 48.19° and the elevation angle is 41.81° above the horizon.

The G159-98 standard specifies the global solar spectral irradiance 'that is incident on a *sun-facing* 37°-tilted surface' (emphasis added). This geometry implies the angle between the receiver normal and the solar azimuth is 0°. Therefore there is an 11.19° angle of incidence between the direct normal beam and the normal to the tilted surface, with the sun's azimuth in the plane of the surface normal.

Note that the solar azimuth is not explicitly defined. The rationale for this lack of precision was provided in BHL83 whose authors stated that for a horizontally homogenous atmospheric model, azimuth geometry was not of concern. In the BHL83 paper, but not in the adopted standard, the sun is explicitly stated as being in the same plane as the normal to the surface (tilted facing the equator at azimuth 180°). This geometry is shown in Fig. 1.

Air mass 1.5 (AM1.5) was selected based on indications that, for locations ranging from Caribou, ME (latitude 46°52′) to Phoenix, AZ (latitude 33°26′), ~50% of solar radiation resources for energy production by photovoltaic conversions systems occurred above or below AM1.5 (Gonzalez and Ross, 1980).

The G159-98 standard for direct normal irradiance specifies a field-of-view solid angle of 5.8° centered on the sun's disk. This includes not only the irradiance from the sun's disk, which is strictly the direct beam irradiance within a 0.53° field-of-view (the average diameter of the solar

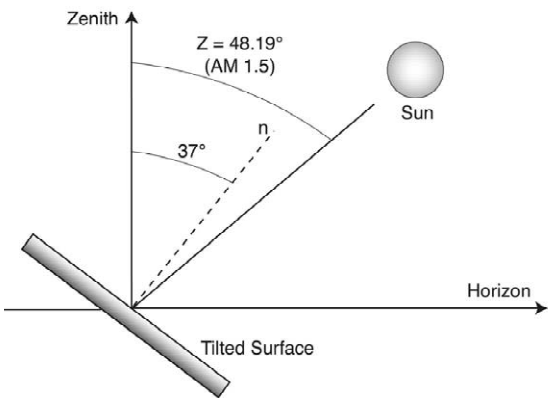

Fig. 1. Reference spectral distributions geometry. The solar azimuth is 180°, in the same plane as the normal to the 'south facing' surface tilted toward the equator (in the Northern Hemisphere). Normal to the tilted plane is *n*.

disk), but also a small contribution (1% broadband average) of diffuse sky radiation. This provision was made to be consistent with usual measuring practices using a '5.8° field-of-view normal incidence pyrheliometer that allows a small amount of circumsolar (diffuse) radiation to be detected' (ASTM, 1987a).

3. ATMOSPHERIC CONDITIONS IN CURRENT STANDARDS

The atmospheric conditions specified in ASTM G159-98 are discussed in detail below but are first summarized as follows.

(a) The 1976 US Standard Atmosphere (USSA) is used. This specifies temperature, pressure, air density, and molecular species density specified in 33 layers starting from sea level (Anon., 1976). The USSA does not define any aerosol profile or content.
(b) An air mass of 1.5 (solar zenith angle 48.19°) at sea level, as detailed above.
(c) An aerosol optical depth or 'turbidity' of 0.27 at 500 nm.
(d) A spectrally constant surface reflectance of 0.2 assuming the surface has a cosine (Lambertian) distribution of reflectivity.

3.1. Standard atmosphere

A description of, and more information on, the USSA can be obtained from the original publication (Anon., 1976). With a sea-level temperature of 15 °C and relative humidity of 45%, it is representative of mid-latitudes during transitional seasons.

3.2. Water vapor and ozone

Integrating the water vapor content in a vertical column in the USSA produces a total equivalent depth of water (or 'precipitable water') of 1.416 cm (rounded to 1.42 cm in the work of Bird and the standards). The ozone content and profile of the USSA is also prescribed, and results in a total equivalent thickness of 0.344 atm-cm in a vertical column (rounded to 0.34 atm-cm in the work of Bird and the standards).

3.3. Aerosol optical depth, turbidity, visibility, and meteorological range

Aerosols strongly affect the propagation of solar radiation through the atmosphere. Aerosols scatter the radiation in a wavelength-dependent manner that is a function of their size distribution. Different quantities have been traditionally used to characterize the effect of aerosols on atmospheric extinction. Aerosol optical depth (AOD) is a direct measure of the attenuation of the incoming direct beam radiation by aerosols at any wavelength. It is also possible to define a broadband AOD and relate it to spectral AOD (Gueymard, 1998; Molineaux *et al*., 1998).

Turbidity is defined as 'any condition of the atmosphere which reduces its transparency to radiation, especially visible radiation. Ordinarily, this is applied to a cloud-free portion of the atmosphere that owes its turbidity to air molecules and suspensoids such as smoke, dust, and haze, and to scintillation effects' (American Meteorological Society, 1980). The earliest appearance of a turbidity 'factor' dates back 80 years (Linke, 1922) and was defined as the number of ideal clean-dry (or 'Rayleigh') atmospheres that would be radiatively equivalent to the real dusty-humid atmosphere. It is therefore necessarily expressed as a number >1 and can be defined either at a specific wavelength or for the integrated spectrum (Konratyev, 1969). The turbidity 'coefficient' was later defined (Ångström, 1929) as the AOD at 1 μm. An ideally clean-dry atmosphere would thus be characterized by a turbidity *factor* of 1 and a turbidity *coefficient* of 0. This historical background is necessary here because 'turbidity' and 'aerosol optical depth' are often used interchangeably. Unfortunately, it appears that wording in the ASTM standards adds to the confusion of these terms by referring to the aerosol effect to 'turbidity at 500 nm' rather than to 'AOD at 500 nm'.

The wavelength dependence of the extinction of aerosols, attributed to Ångström, is expressed as

$$\tau(\lambda) = \beta(\lambda/\lambda_o)^{-\alpha} \qquad (1)$$

where $\tau(\lambda)$ is the extinction coefficient at wavelength λ, referred to as the spectral AOD. β is the 'Ångström turbidity coefficient' mentioned earlier, equal to $\tau(\lambda)$ for $\lambda = \lambda_o = 1$ μm. α is related to the size of the aerosol particles, ranging in practice from about 0 (very large particles) to 2.6 (very small particles), usually called the 'Ångström turbidity exponent', 'Ångström exponent', or 'wavelength exponent'.

In ASTM G159-98, and the previous ASTM versions of the standard spectra, the 'turbidity at 500 nm' equal to 0.27 was selected to represent the aerosol conditions 'estimated to be reasonable average for the 48 contiguous states of the US over a period of a year'. The validity of this statement, as well as the reasoning behind the selection of this particular value, are discussed below.

This turbidity is said to 'correspond to a sea-level meteorological range of 23 km', but deeper scrutiny is needed here. Visibility and meteorological range indicate the distance in a horizontal direction at which one can discern and identify an object through the atmosphere. They are affected by the aerosol optical depth contributing to extinction in the lower atmosphere (where aerosols are concentrated). Visibility and meteorological range are smaller for high turbidity and larger for low turbidity conditions. Confusingly, 'meteorological range' and 'visibility' are not physically identical, but are often used interchangeably in the literature. Visibility is the greatest range at which it is just possible to discern and identify a dark object against a daytime horizon sky, as regularly reported by human observers at airports. It is of a subjective nature and depends on the existence of a range of appropriate markers at regularly spaced and known distances.

Meteorological range, V, is objectively defined by the Koschmieder formula (Koschmieder, 1924)

$$V = (1/\kappa)\ln(1/\varepsilon) \tag{2}$$

where κ is the total extinction coefficient (sum of molecular and aerosol extinction) at 0.55 μm, in units of km^{-1}, and ε is a threshold contrast whose value is set equal to 0.02 (as mentioned in the early standards ASTM E891/E892).

Eq. (2) can be also be used to provide an *objective* definition of visibility but then ε must be increased to 0.05, as mentioned in the revised standards (ISO, 1992; ASTM, 1998a). The ratio of the two determinations is $\ln(0.02)/\ln(0.05) = 1.306$. Given an observer's estimate of visibility, V_{ob}, in km, the empirical relationship between V and V_{ob} reported by Kneizys *et al.* (1980) is

$$V = (1.3 \pm 0.03)V_{ob} \tag{3}$$

confirming the validity of Eq. (2) and of the relative values of ε.

While the G159-98 standard prescribes a 23-*km meteorological range*, in the paper serving as the basis of the standards, BHL83, the authors specify that they used a rural aerosol model (Shettle and Fenn, 1975) and that 'a sea level meteorological range of 25 km was used, which resulted in total aerosol optical depths in a vertical column from sea level (turbidities) of 0.37 at 0.368 μm wavelength, 0.27 at 0.500 μm wavelength, and 0.14 at 0.862 μm wavelength'. In a subsequent paper (HBR85), the same information is slightly—but more confusingly—reworded, stating that these AODs are calculated using 'a sea level visibility (meteorological range) of 25 km'.

Using a different—but related—source (Elterman, 1968), this meteorological range of 25 km results in a sea-level extinction coefficient of $0.158\ km^{-1}$ at 0.55 μm, and an AOD of 0.250 at 0.55 μm and 0.264 at 0.5 μm. The latter value is reasonably close to that later used by Bird (0.27). The models of atmospheric aerosols and optical properties described in subsequent work (Shettle and Fenn, 1975) also use an extinction coefficient of $0.158\ km^{-1}$ at 0.55 μm. This is claimed as 'corresponding to a surface visibility of about 23 km . . . to be compatible with the Elterman and LOWTRAN models'. Shettle and Fenn also mention that at the time (1975), the 23-km rural aerosol distribution used in LOWTRAN3 was a preliminary version of their 'present model'.

LOWTRAN refers to the 'low resolution' atmospheric transmission code developed by the Air Force Geophysical Laboratory (AFGL) in the late 1970s, which then evolved up to version 7 (Kneizys *et al*., 1988), and further to the MODTRAN (for moderate resolution) transmission code, version 1 to the current version 4 (Berk *et al*., 1989, 1999; Anderson *et al*., 1993). The LOWTRAN and MODTRAN codes will be discussed in more detail in Section 5.1.

From the discussion above, there is a discrepancy between the meteorological range (25 km) specified in the BHL83 and HBR85 publications and the resulting ASTM standards (23 km). Confusion also results from inconsistent wording (visibility vs. meteorological range; turbidity vs. AOD) and inconsistent numerical correspondence between meteorological range and AOD. A possible reason for this discrepancy may be that the 23 km—rather than 25 km—meteorological range has become one of several key 'reference' conditions presently utilized by the modern atmospheric transmission modeling community.

3.4. Extraterrestrial spectrum

In BHL83, the authors describe 'old' and 'new' spectral calculations. The NASA/Thekaekara extraterrestrial (or 'AM0') spectrum (Thekaekara, 1974) was used for the 'old' spectra and in the 1982 version of ASTM E891 and E892. The same Thekaekara spectrum was adopted as an ASTM standard for AM0 in 1973 (ASTM, 1973).

The 'new' BHL83 spectra were computed

using a 'revised' AM0 spectrum (Neckel and Labs, 1981), provided as personal communication to Bird and Hulstrom in 1981 (Riordan, 1987). Comparing the 'new' spectra in BHL83 and the ASTM 1987 spectra, it is clear that the 1987 spectral standards are the 'new' spectra computed in BHL83. The significant differences between the 1982 and 1987 versions of the spectra are due to the choice of a different AM0 irradiance in each case. A discussion of the extraterrestrial spectra used by Bird and collaborators from 1980 to 1987 is given elsewhere (Riordan, 1987).

The ASTM E490-73 spectrum was recently revised (ASTM E490-00) to replace the Thekaekara spectrum with modern data assembled from various sources (ASTM, 2000). This extraterrestrial spectrum is different from, but mostly consistent with, the Neckel and Labs AM0 spectrum used in BHL83 to produce the 1987 ASTM AM1.5 modeled spectra. Extraterrestrial spectra are discussed in Section 5. Fig. 2 shows the Neckel and Labs AM0 spectrum at the resolution used in BHL83 and the existing direct and global hemispherical spectra in the G159-98 standard.

3.5. Reference spectral calculations

The 1982 and 1987 ASTM reference spectra were modeled using then current (circa 1975–1980) aerosol extinction models based on Mie theory. They assumed a bi-modal, log-normal aerosol size distribution, with a complex index of refraction which varies with wavelength, displayed explicitly in Table 1 of BHL83.

Bird used a Monte Carlo radiative transfer code (BRITE) described elsewhere (Collins *et al.*, 1972; Bird and Hulstrom, 1979; Blättner, 1983) to compute transmitted solar spectral irradiances. Bird and Hulstrom ran the BRITE code at the Solar Energy Research Institute (SERI), now the National Renewable Energy Laboratory (NREL), on Control Data Corporation CDC 6600 machines. They also used various versions of LOWTRAN, and used the Shettle and Fenn (1975) aerosol model with BRITE.

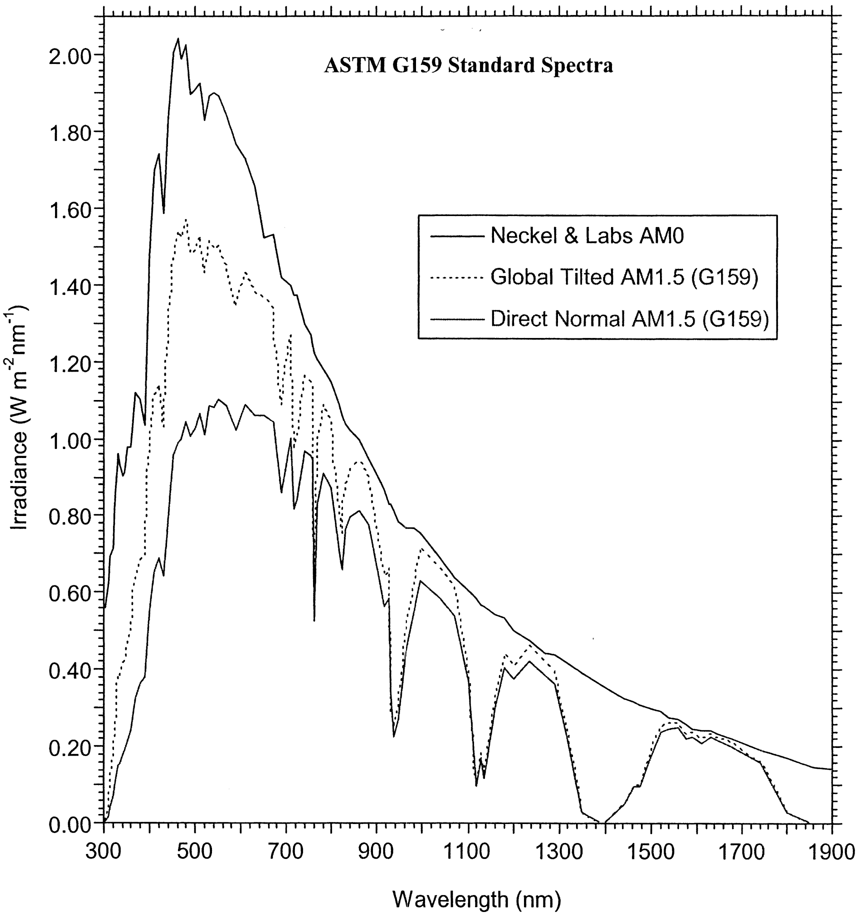

Fig. 2. Neckel and Labs AM0 extraterrestrial spectrum and ASTM G159 (direct normal and global, 37° sun-facing tilted) terrestrial spectra as tabulated in the current standard.

As described in BHL83, aerosol extinction (scattering + absorption), water vapor absorption, mixed gas absorption and ozone absorption were all computed by integrating over the 33 layers of aerosol density profiles and standard atmosphere constituents. Modeled terrestrial spectra were developed for various combinations of atmospheric parameters and air mass, including the combination eventually selected for the reference spectra. The BHL83 authors used their own parameterization of the spectral dependence of Rayleigh scattering. Computations were performed for 122 irregularly spaced wavelengths with a resolution of 20 cm^{-1}, corresponding to 0.2-nm resolution at 300 nm, and to 30-nm resolution at 4000 nm (Table 1). This 20 cm^{-1} resolution was the same as that in LOWTRAN and probably the best possible in atmospheric calculations at the time. In BHL83 the authors stated that 'The new spectra should resemble 0.005 μm [5 nm] resolution data'. However, Bird also recognized that 'it would be desirable to have the resolution constant in wavelength rather than wavenumber for this application, but that was beyond the scope of this work. As an alternative, we have selected wavelengths that appear to reproduce 10-nm resolution experimental data' (Bird, 1984). In another report (Riordan, 1987), this 10-nm resolution smoothing process is also confirmed, in apparent contradiction with the BHL83 statement given above. The 'effective' 5-nm or 10-nm resolution is relatively low and this explains why results were provided at very irregular intervals, which were chosen to capture atmospheric absorption features.

The original computed results with BRITE extended from 305 to 2450 nm (Bird and Hulstrom, 1983; Bird *et al*., 1983). The source of the additional data (between 2450 and 4045 nm) that are provided in the standards is not described in detail. However, HBR85 mentions parallel work done at NASA in the late 1970s. This led us to discover that the 'complementary data' had been simply extracted from the spectral results in Tables 4 and 6 of a NASA report (Mecherikunnel and Richmond, 1980). These DNI results were obtained using a simpler spectral model than that used by Bird *et al.* (e.g. using Eq. (1) rather than a more sophisticated aerosol submodel), for similar—though not identical—atmospheric conditions (Thekaekara's extraterrestrial spectrum, AM1.5, 2 cm precipitable water, 0.34 atm-cm ozone, $\alpha = 1.3$, and $\beta = 0.02$). The same values for the infrared tail of the spectrum were used again without modification when E891 was modified in 1987. The complementary infrared data for the hemispherical spectrum in E892 are only slightly different from those in E891, and have been most probably obtained by empirically correcting the corresponding numerical values of the NASA direct spectrum.

Table 1. Wavenumber passband resolution at various wavelengths

Wavelength μm	Wavelength nm	Wavenumber cm^{-1}	Nanometres resolution at 1 cm^{-1} (MODTRAN)	Nanometres resolution at 20 cm^{-1} (LOWTRAN)
0.25	250	40000	0.006	0.125
0.30	300	33333	0.010	0.200
0.50	500	20000	0.025	0.500
1.00	1000	10000	0.100	1.996
4.00	4000	2500	1.50	30.00
5.00	5000	2000	2.50	49.50
10.0	10000	1000	9.99	196.08
50.0	50000	200	248.76	4545.45

4. ISSUES AFFECTING THE USEFULNESS OF CURRENT STANDARD SPECTRA

Several deficiencies and issues associated with the G159-98 reference spectra have become apparent since their adoption. In this section, we detail these concerns, for use as rationale to implement the recommendations for updates discussed later.

4.1. Reproducibility

It is not possible to reproduce the existing G159-98 spectra using the original software tools and input files used by Bird and co-workers in 1982–1985. The BRITE computer code used to generate the reference spectra was engineered to operate using a significant number of binary coded data tapes, and using machine-specific capabilities of the CDC 6600 mainframe computers. NREL's attempts to convert the data tape binary format code to be compatible with various minicomputers that replaced the CDC mainframe were unsuccessful due to resource limitations and the non-standard machine-specific binary input file tapes used in the CDC version of the code.

Nevertheless, given the information in the current standards and the original research publications, it is possible to closely approximate the existing standard spectra using modern spectral models, current aerosol profiles, and atmospheric layered data of USSA. Moreover, it becomes possible to generate new reference spectra for different atmospheric conditions.

4.2. Solar geometry

The relative sun–receiver geometry stated in the G159-98 standard is confusing and not perfectly defined. Only in the original BHL83 paper is it explicitly stated that the azimuth angle between the sun and the normal to the receiver is zero. This implies the exact incidence angle of the direct beam to the receiver is 11.19°. (The description of the geometry in G159-98 only implies the *minimum* possible incidence angle is 11.19°.) The standard contains no information on the spatial distribution of the diffuse radiation field that contributes, with the direct beam, to the hemispherical spectral distribution. For some applications (e.g. PV systems with tracking concentrators), it would be desirable to increase or decrease the effective field-of-view of the irradiance, which in turn modifies the circumsolar contribution, particularly at shorter wavelengths. The present standards do not describe the earth–sun geometry with respect to day of the year, earth–sun radius vector, implying mean values for the distance and extraterrestrial irradiance.

4.3. Spectral range and ultraviolet

While the spectral range of the reference standards covers the region of most use and interest to the photovoltaic community, there are serious deficiencies in the shortwave region below 400 nm. There are no data at wavelengths shorter than 305 nm, and only 10 wavelengths below 350 nm, where extremely steep irradiance variations are remarkable. Ultraviolet (UV) radiation is of great importance in the degradation of materials and the fields of solar detoxification of hazardous materials, photobiology and atmospheric physics. UV photons have been measured below 295 nm in the terrestrial environment (Blumenthaler, 1993). The standard spectra should reflect a representative population of these wavelengths, and have sufficient resolution to adequately represent this important spectral region.

4.4. Spectral resolution (step size)

The G159-98 reference spectra were computed at 122 irregular wavelengths, selected to capture the main absorption features of the atmosphere. The irregular spacing makes it inconvenient to perform calculations with respect to higher resolution and/or evenly spaced spectral data. Moreover, different integration methods produce slightly different broadband irradiances, as shown in HBR85. For instance, the *rectangular rule* provides a total (0.305–4.045 μm) irradiance of 768.15 W/m^2 for the direct normal spectrum and 963.56 W/m^2 for the hemispherical tilted spectrum. If using the *trapezoidal rule*, these numbers, respectively, change to 767.17 and 962.53 W/m^2, or to 768.31 and 963.75 W/m^2 if using the *modified trapezoidal rule*.

Even though HBR85 did not take a position on which technique would be preferable, the ASTM standards retained the latter one (modified trapezoidal rule), but without any justification for this choice. In any case, it is conceivable that different users may obtain slightly differing results if trying to integrate small parts of the spectrum in very narrow bands whenever interpolation is necessary. While BHL83 and HBR85 recommended linear interpolation as acceptable for filling in data points, reference spectra with appropriate uniform step sizes would be more straightforward to use, and more accurate.

4.5. Spectral resolution (passband)

The spectral resolution, or passband, representing the ASTM G159-98 spectra is loosely stated as computed for 20 cm^{-1} resolution. Table 1 shows this resolution represents an extremely wide range of passbands, from 0.125 nm at 250 nm to 50 nm at 5000 nm. It is relatively easy to ‘degrade’ a high resolution (1 cm^{-1} resolution or better) spectral data file with a given filter or smoothing function shape, with a well-defined full width half maximum (FWHM) passband by performing the convolution integral of spectrum and the passband function. Given an adequate high-resolution spectrum, and the filter function or monochromator slit function used in a measurement, comparison with measurements and modeled spectral data would be more accurate and easier to interpret. The existing spectral standards do not address the issue of spectral passband in sufficient detail to categorically state what the spectral passbands represented by the data are.

4.6. Atmospheric parameters

The atmospheric profiles of USSA determine the ozone, uniformly mixed gases, and water vapor concentrations used in computing the reference spectra. As noted above, the Shettle and Fenn rural aerosol model used by Bird was a ‘preliminary’—but significantly differing—version of a now standardized set of aerosol profiles (Shettle and Fenn, 1979) used by the atmospheric radiative transfer community, particularly in the LOWTRAN (since version 5) and MODTRAN code families. As mentioned earlier, the reference spectra standard refers to a 'turbidity' (actually an AOD) of 0.27 at 0.50 μm and a 23-km meteorological range, while the primary reference document (BHL83) refers to a meteorological range of 25 km. These are only the first points of confusion that must be reconciled with current knowledge.

When a meteorological range of 23 km is used, MODTRAN (v.4) reports an AOD of 0.3571, and thus predicts a less energetic irradiance than the G159-98 direct normal spectrum (by about 20% in the visible). Reciprocally, to obtain an AOD of 0.27 at 0.5 μm, a meteorological range of 31.1 km needs to be considered in MODTRAN, and this produces a direct spectrum consistent with the existing standard. These findings imply that either the aerosol profiles used to produce the 1987 ASTM reference spectra deplete the incoming radiation less than the currently accepted rural aerosol profile (Shettle and Fenn, 1979) for the same 23-km meteorological range, or that the reference spectra were based on a longer meteorological range.

4.7. Accuracy

Even though the *overall* accuracy of the standard spectra can still be considered as very good, some concerns might be raised because of the following issues.

(i) As mentioned earlier, the small number of wavelengths limits the accuracy of the modeled irradiance in those spectral bands where strong absorption lines with considerable structure exist.

(ii) BRITE used absorption coefficients from the 1978 AFGL line parameter data obtained from spectroscopic measurements (Rothman, 1978), for use in its *band absorption model*. Considerable progress has been made on both these experimental and modeling fronts. Bird (1984) also acknowledged that 'a few absorption coefficients have been adjusted to agree with experimental data when varied from the results of rigorous codes'. The extent of these 'adjustments' is not known, nor are their spectral regions.

(iii) These original line parameter data were degraded to 20 cm^{-1} resolution prior to their integration into BRITE. This might have introduced an exaggerated smoothing in the near-IR part of the spectrum, as can be inferred from Table 1. The selection of specific wavelengths was also an empirical process, 'to reproduce 10-nm-resolution experimental data' (Bird, 1984), the accuracy of which is not known.

(iv) The stochastic nature of this Monte Carlo code introduced uncertainties of its own. In a detailed account of his modeling approach (Bird, 1982), the author stated that 'up to 10 wavelengths can be modeled simultaneously in a single computer run. The only assumption is that the aerosol phase function is constant over the wavelength interval being considered'. This issue might induce some wavy/discontinuous—rather than smooth—spectral variations, or 'statistical fluctuations', in the diffuse irradiance spectrum (Bird, 1982). This was demonstrated to be the case, at least for the circumsolar diffuse irradiance, in Fig. 14 of Gueymard (2001a).

(v) The AM0 spectrum (Neckel and Labs, 1981) that was used to produce the latest standard spectra is now outdated. It is difficult to evaluate the accuracy of this older spectrum with reference to more recent data because of their differing resolution. Using indirect comparisons (Riordan, 1987; Thuillier *et al.*, 1998), it can be inferred that most of the Neckel and Labs spectrum is within the current uncertainty estimate of ≈2% (Thuillier *et al.*, 1998), with occasional differences within limited spectral regions of up to 5%, or possibly more.

(vi) The ground albedo is specified as 0.2, which is a relatively valid assumption for most surfaces, when considering *broadband* averages. However, most natural surfaces exhibit highly variable spectral reflectance, with very low albedo values in the UV (except for snow) generally below 0.05, and with peaks in the near infrared (800–1500 nm) that exceed the typical broadband global albedo of 0.2. Moreover, all natural surfaces depart, at least slightly, from the ideal Lambertian reflection process assumed in the standards. Therefore, a sun-facing surface will receive more reflected radiation than a surface opposed to the sun, for otherwise identical conditions.

(vii) The ratio of the present normalized and unnormalized hemispherical and direct spectra produces a wavelength-dependent ratio, probably related to rounding and issues of significant digits in the ratio components, but other sources for the nonconstant ratios are possible.

4.8. Data errors

Some typographical errors appear when comparing the original irradiance tabulations in BHL83 to the tabulated standard spectra in either

ASTM or ISO publications. For example, two numerical errors (at 0.46 and 0.69 μm) can be detected in ASTM E891-87, six errors (at 0.71, 0.7675, 1.1208, 1.20, 1.558, and 1.6788 μm) can be found in ASTM E892-87, and again six errors (at 0.46, 0.69, 0.71, 0.7675, 1.558, and 1.678 μm) appear in the ISO standard (ISO, 1992). Some of these errors were corrected when E891 and E892 were replaced by G159-98, but other errors were made (e.g. at 0.350 μm).

4.9. Summary

Given the above state of affairs, the authors suggest using current well documented and widely accepted atmospheric radiative transfer models to implement, document, and validate revised reference spectra to meet current needs. Detailed documentation of input parameters for such models would allow users to reproduce the reference spectra at will, and easily perform research on the impact of spectral distributions departing from the standards. In the next section, we discuss this approach with respect to spectral models of simple, moderate, and highly complex nature.

5. SPECTRAL ATMOSPHERIC TRANSMISSION MODELS

There have been significant improvements in atmospheric radiative transfer models in the years since the reference standard spectra were first adopted. Improved parameterization of the absorption properties of the atmosphere's gaseous constituents and modeling of the properties of aerosols in the atmosphere are some of the essential advances made. Models can be classified as simple, moderately complex, and very complex, depending on the balance between empirical and theoretical principles incorporated into them (see the review in Gueymard, 2001b).

5.1. Rigorous models: LOWTRAN, MODTRAN, and FASCODE

MODTRAN is an example of a very complex spectral transmission model. The FORTRAN source code for MODTRAN is comprised of over 52,000 lines of code. MODTRAN was developed by AFGL, evolving over the past 30 years from the LOWTRAN series of atmospheric transmission models (McClatchey, 1979), also developed by AFGL. Both LOWTRAN (since version 6) and MODTRAN are 'band model' implementations of the highest resolution atmospheric transmission model, FASCODE, also developed at AFGL (Clough *et al*., 1981; Anderson *et al*., 1993, 1994, 1996).

FASCODE is a line-by-line (LBL) transmission model, making use of fundamental radiative transfer theory and the quantum mechanical properties (due to molecular absorption, scattering, bending, rotation, and isotopic concentrations) of atmospheric constituents. The catalog of all lines and their fundamental properties is the HITRAN database, assembled and maintained by the Harvard Smithsonian Astrophysical Observatory (SAO) (Rothman *et al*., 1992, 1998). HITRAN is considered an international standard database for molecular spectroscopy. Over 1 million spectral absorption lines for 38 gaseous constituents of the earth's atmosphere, along with 27 additional molecules for which absorption cross sections only are given, are catalogued in HITRAN. FASCODE is a radiative transfer algorithm to model atmospheric transmission over very narrow bandwidths. FASCODE reproduces results resolved line-by-line, wavelength-by-wavelength. LOWTRAN and MODTRAN utilize computationally-efficient 'band model' or 'transmission function' approximations to produce an 'equivalent absorption' for use by the radiative transfer code. The highest computational resolution MODTRAN produces is 1 cm^{-1}, compared to 20 cm^{-1} for the previous LOWTRAN family. The highest *effective* resolution in the MODTRAN results is quoted as 2 cm^{-1} (Wang and Anderson, 1994). Example relative spectral (passband) resolution of each model at various wavelengths is shown in Table 1.

In their original release, the MODTRAN, LOWTRAN, and FASCODE source FORTRAN codes can be compiled on different machines and used in a batch mode. The AFGL has now licensed these codes as commercial user-friendly products for use on personal computers through the ONTAR Corporation (9 Village Way, North Andover, MA 01845-2000 USA, http://www.ontar.com). In any case, these models require careful reading of the documentation, extensive input parameter prescription, and some expertise in atmospheric physics and radiative transfer to produce meaningful results. While default profiles and parameters are available, the user can prescribe an arbitrary set of parameters (including clouds, fog, rain, smoke, etc.) and geometry for calculating atmospheric radiance or direct beam transmission. However, these models cannot directly provide the diffuse irradiance incident on a tilted receiver, and this constitutes a major limitation for the envisioned applications. In other words, a global tilted spectrum (such as E892) *cannot* be generated with LOWTRAN or MODTRAN.

5.2. Simple spectral models: SPCTRAL2

Complex, rigorous atmospheric transmission models such as MODTRAN are not appropriate for all applications, such as solar energy system engineering. A simpler parameterized or semi-empirical model can usually meet the users needs. A number of models have been published in the literature (Brine and Iqbal, 1983; Bird, 1984; Justus and Paris, 1985; Matthews *et al*., 1987; Nann and Riordan, 1991; Gueymard, 1993), based for the most part on the transmittance model of Leckner (1978). In particular the SPCTRAL2 model developed by Bird and co-workers at SERI/NREL (Bird, 1984; Bird and Riordan, 1986; Riordan, 1990), has been extensively distributed and evaluated (see, e.g., Utrillas *et al*., 1998).

SPCTRAL2 relies on the product of empirical, closed-form transmission functions for the most important elements of atmospheric extinction: air molecules, ozone, water vapor, uniformly mixed gases, and aerosols. The product of the transmission functions to produce the transmitted beam irradiance modifies the extraterrestrial spectral direct beam irradiance. Simple theoretical relations are used to estimate the distribution of sky and ground reflected radiation. The SPCTRAL2 model is easily implemented in about 120 lines of source code in FORTRAN. Alternatively, the equations are simple enough to be implemented in personal computer spreadsheets.

Bird developed the SPCTRAL2 model at the same time (1980–1985) that he was using BRITE to develop the ASTM reference spectra. Bird used BRITE to validate the SPCTRAL2 model, and compared it with several of the other simple models cited above. Many of the SPCTRAL2 model wavelengths are common with the ASTM G159 spectra, but there is not an exact one-to-one correspondence. Because SPCTRAL2 and BRITE are indeed very different models, they do not produce exactly the same result at a particular wavelength. Thus, SPCTRAL2 can only be used to generate an approximation to the reference spectra (Bird and Riordan, 1986). Because the SPCTRAL2 model has never been updated since its original release (Bird, 1984), its performance might appear to have changed over time, compared to continuously evolving atmospheric codes such as MODTRAN.

5.3. Moderately complex model: SMARTS

To fill the gap between the two previous categories of models, Gueymard developed a more complex model than SPCTRAL2 based on new and more detailed parameterizations of the different extinction processes in the atmosphere, including temperature and relative humidity effects (Gueymard, 1994, 1995, 2001a,b, 2002). More accurate absorption coefficients derived from recent spectroscopic data are included.

5.3.1. Extraterrestrial spectra. The user of SMARTS may choose from seven alternative extraterrestrial spectra. In its most recent versions (2.9 to 2.9.2; note that these versions are strictly equivalent with respect to all results discussed below), the main default is a revised, synthetic extraterrestrial spectrum with 2002 wavelengths between 280 and 4000 nm (Gueymard, 2002). In the UV, where different instruments on board various spacecrafts have been providing data for years (see, e.g., Brueckner *et al*., 1993), the revised spectrum has been developed from different sources, including unpublished data. For the rest of the spectrum, the main source of data is from Kurucz (1995). (The Kurucz spectrum has also been an option in MODTRAN since version 3.5, and has been used to produce ASTM E490-00.) The spectral step size of the extraterrestrial spectrum is 0.5 nm from 280 to 400 nm, 1 nm from 400 to 1702 nm, and 5 nm above 1705 nm. The effective spectral resolution at each computed point is approximately the same as the step size.

As mentioned above, there is an ASTM extraterrestrial spectrum, E490-00, which in this latest revision is a combination of different sources including the Kurucz spectrum (ASTM, 2000). All three of the extraterrestrial spectra mentioned above (SMARTS, E490-00, and Neckel and Labs) differ from each other only slightly. It should be expected that the SMARTS and E490-00 spectra be in excellent agreement although they do not have the same resolution.

5.3.2. Spectral resolution. The terrestrial solar spectra computed by SMARTS have a spectral resolution equivalent to that of the wavelength interval (0.5 to 5 nm). Parameterizations in the SMARTS model are based on high-resolution ($1\ \mathrm{cm}^{-1}$) MODTRAN results subsequently 'degraded' or smoothed to the SMARTS model wavelength interval. The process relies on energy conservation over short spectral intervals. For example, to obtain the irradiance at 1000 nm, for which the target resolution is 1 nm, all Modtran higher-resolution results within the interval 999.5 to 1000.5 nm are averaged using the trapezoidal rule. Hence, equal energy is predicted by both codes over this 1-nm interval. This approach emulates the measurement of spectral data with a monochromator with a rectangular FWHM passband equal to the wavelength interval for the spectral passband of the instrument.

5.3.3. Atmospheric profiles. The SMARTS model incorporates 10 widely used 'reference' atmospheric profiles, including the USSA. SMARTS accounts for Rayleigh scattering, absorption from 19 different gases (e.g. ozone, nitrogen dioxide, and water vapor), and aerosol extinction properties (Shettle, 1989; Shettle and Fenn, 1979), using individual parameterizations of the 'optical mass' for each constituent. Through the use of these optical masses rather than only zenith angle, the limitations of the plane-parallel simplified assumption can be essentially overcome. (As a consequence, the zenith angle to be used for an air mass of 1.5 is slightly larger than what was reported in ASTM G159 for a simplistic plane-parallel atmosphere, i.e. 48.24° rather than 48.19°.)

Some of the absorption functions are parameterizations based on MODTRAN components, or derived from analysis of multiple MODTRAN model results. Thus, SMARTS may be viewed as a 'simplified' or 'parameterized' MODTRAN model. The source code listing is only about 4200 lines of FORTRAN code or 150 kilobytes (kb); yet the program provides much of the flexibility of MODTRAN with improved accuracy and capabilities over the SPCTRAL2 model.

5.3.4. Validation. As SMARTS partially consists in a simpler parameterization of the different MODTRAN submodels, extensive comparisons between MODTRAN and SMARTS model results have been performed, and found quite accurate, as one might expect. An example of this appears in Fig. 3, which compares the atmospheric transmittance predictions of SMARTS (v.2.9) and MODTRAN (v.4). The latter's output values in wavenumbers have been resampled and degraded using the procedure outlined above, so that wavelength-by-wavelength comparisons can be performed. It is found that, for the selected atmospheric conditions at least (those of G159-98 in this case, although comparisons for other conditions have been shown to be consistent with the results presented here), SMARTS and MODTRAN agree within generally 1%. Exceptions to this very small relative difference may occur in a few strong absorption bands, where transmittance is close to zero, and in some weaker bands caused by absorbing gases considered in SMARTS but not in MODTRAN, or vice versa. These slight discrepancies have no significant effect on the predicted irradiances, which can thus be deemed 'equivalent'.

Still using MODTRAN4 as a benchmark, Fig. 4 provides an illustration of the gain in accuracy (of about an order of magnitude) that results from using SMARTS rather than BRITE to predict the direct normal spectrum for the conditions of the current standard (G159-98).

Comparison with other rigorous atmospheric radiative models such as the spherical harmonics code of Braslau and Dave (1973) have been performed and show excellent agreement (Gueymard, 2001a).

An important aspect of the performance assessment (or 'validation') of a radiative model consists of detailed comparisons of predictions with carefully measured data of irradiance under 'known' atmospheric conditions. In practice, however, at least some of the necessary inputs to a radiative model are not accurately known and must be estimated in a way or another, thus increasing the model predictions' uncertainty. Conversely, no instrument is perfect and may suffer from calibration, operational, or other problems.

With these limitations in mind, a series of spectroradiometric measurements at the Florida Solar Energy Center (FSEC) and NREL can be used as a reference for such a test. One of the instruments used in this experimentation is a temperature-controlled Li-Cor LI-1800, with a 6-nm FWHM and a scan time of 27 s. A detailed characterization of its optical performance for the measurements reported here is described elsewhere (Myers, 1989). The SMARTS predictions (with version 2.9.2) of both direct normal and global tilted irradiance appear to be largely within the instrumental uncertainty over the spectroradiometer's spectral range (300–1100 nm). Fig. 5 presents a typical example of the numerous such comparisons that have been performed, using data measured at the sea-level site of FSEC, Cape Canaveral, FL. For the conditions of the particular clear day shown here (28 February 1988), the air mass was 1.47; the AOD at 500 nm was estimated to be 0.17 and precipitable water 1.1 cm. (No fine tuning of these important variables, or other input variables, has been attempted.)

Other tests conducted in Valencia, Spain with the same model Li-Cor instrument demonstrated SMARTS to be more accurate with respect to the measured data than SPCTRAL2 (Utrillas *et al*., 1998).

To assess the performance of SMARTS with

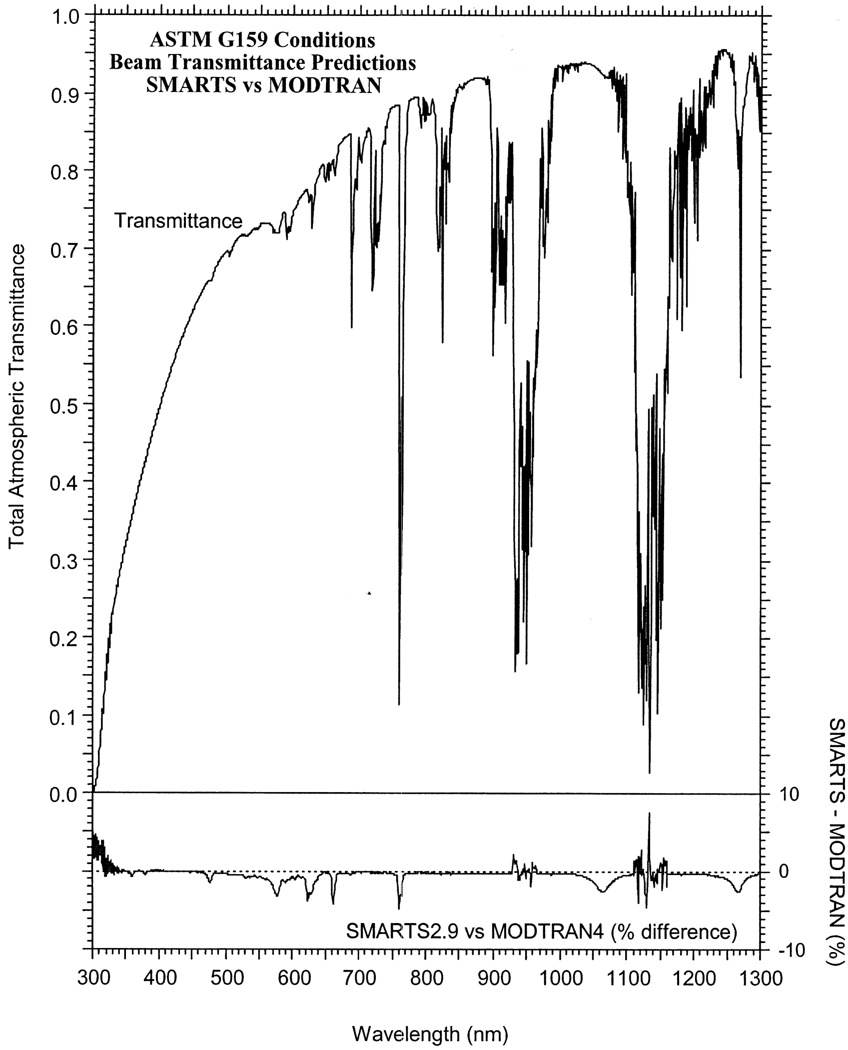

Fig. 3. Atmospheric transmittance predicted by SMARTS v.2.9 and MODTRAN v.4 for the same ASTM-G159 conditions. Bottom panel shows percent deviations of the SMARTS transmittance predictions relative to those of MODTRAN. Inclusion of absorbers not accounted for in MODTRAN explains most of the negative deviations.

respect to a larger spectral range and possibly more accurate measurements, we, at the NREL site in Golden, CO (altitude 1829 m), recently started episodic measurements of clear sky spectral distributions over a range of air masses with an Optronic Laboratories OL-750 spectroradiometer. It has an effective spectral passband of 5 nm, and measurements are made in 5-nm increments over its full spectral range (300–2500 nm), which is far larger than that of the LI-1800. The OL-750 is only deployed when conditions permit and is manually operated. This is in addition to the spectral scans recorded automatically every 5 min by two LI-1800 instruments, one measuring DNI and the other latitude-tilted irradiance. Both the OL-750 and the LI-1800 are equipped with a 5° collimator for DNI measurements. For the single-day preliminary results reported here (18 October 2002), ancillary data from the NREL Solar Radiation Research Laboratory provided sun-photometer-based AOD estimates of about 0.130 at 368 nm, 0.067 at 500 nm, and 0.052 at 778 nm. Precipitable water was about 0.45 cm. The SMARTS spectral model was run with Gaussian smoothing to simulate the 5-nm resolution of the spectroradiometer. Fig. 6 shows the comparison between model and measured spectra, suggesting generally excellent agreement. Integration of the model results over the effective passband may fortuitously reduce random differences between the computed and measured data. Spectrometer irradiance calibration uncertainty with respect to National Institute of Standards and Technology (NIST) spectral irradiance standard lamps, (typi-

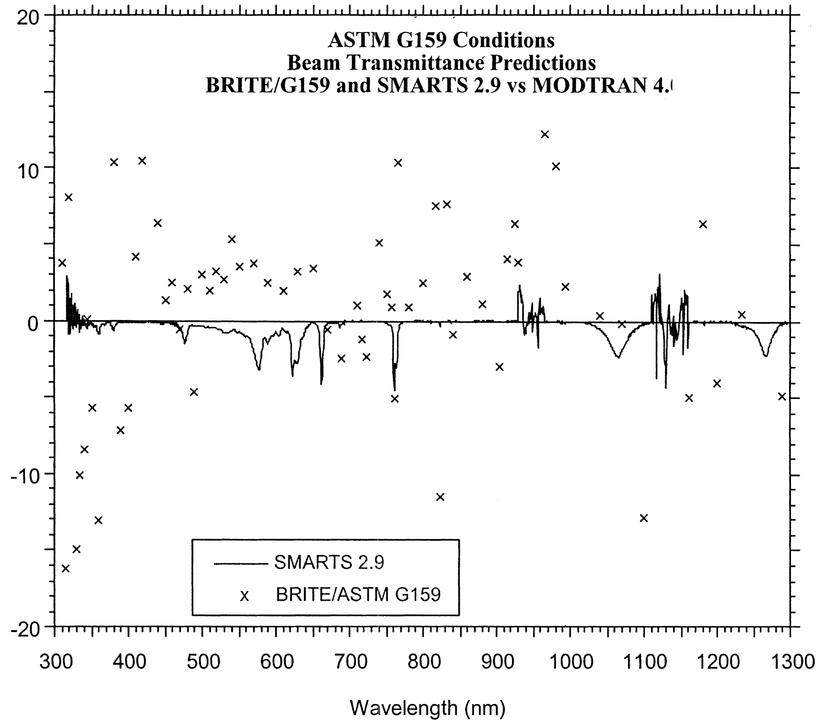

Fig. 4. Relative atmospheric transmittance percent difference predicted by SMARTS v.2.9 and BRITE, compared to MODTRAN v.4 for the same ASTM-G159 conditions.

cally ±2–4%; Walker *et al.*, 1987) temperature effects, and wavelength accuracy and repeatability (±0.5 nm specification) contribute to some of the measurement 'outliers'. Another source of error results from the relatively long time (120 s) needed to perform a complete scan, during which the sun position and atmospheric conditions can vary. Despite this scan time nearly five times longer than the LI-1800 instrument, the agreement between the SMARTS predictions and the OL-750 spectral scans is a lot closer than with those obtained with the collocated LI-1800 instrument.

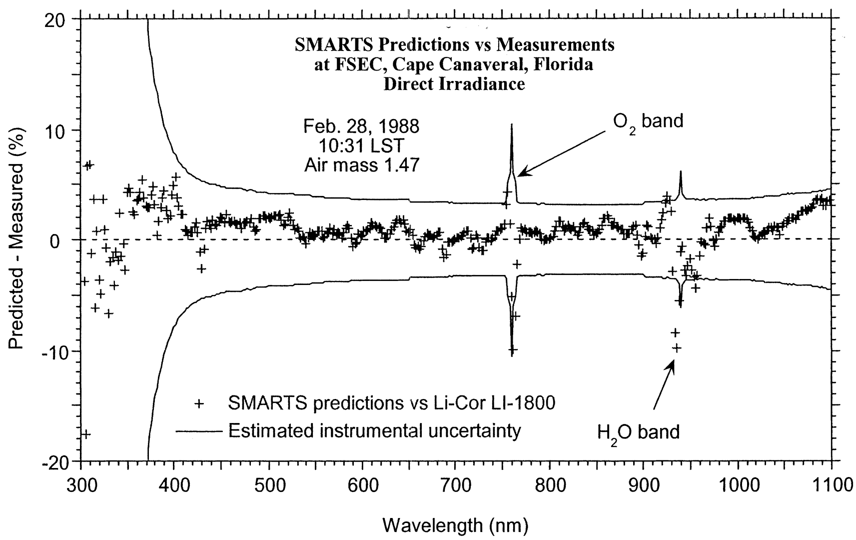

Fig. 5. Percent difference between smoothed SMARTS predictions and spectroradiometric measurements (Li-Cor LI-1800) for direct normal irradiance under clear conditions at FSEC, Cape Canaveral, FL. The instrumental uncertainty envelope applies to this particular instrument (Myers, 1989).

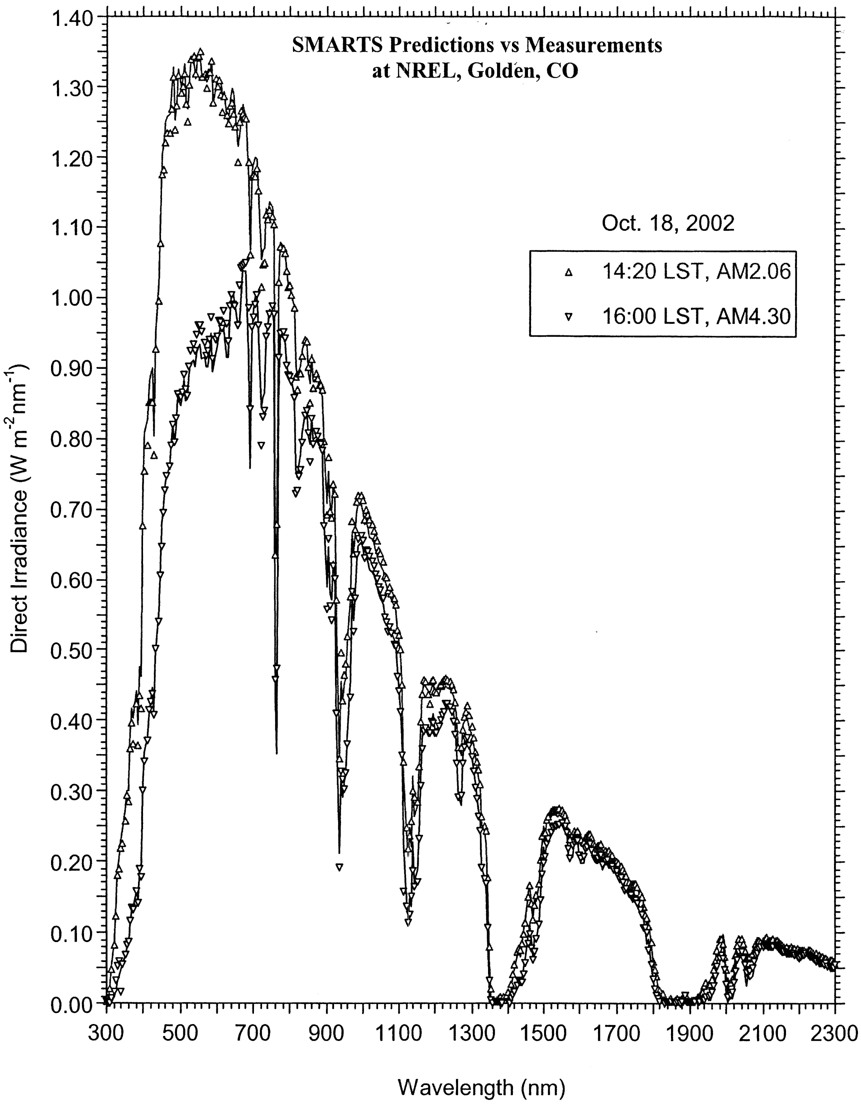

Fig. 6. SMARTS DNI predictions smoothed to 5-nm resolution (lines) and OL-750 spectrometer measurements (symbols) at 5-nm resolution at air mass 2.06 and 4.30 at NREL, 18 October 2002.

This is demonstrated in Fig. 7, which shows similar results to that of Fig. 5, but for the same AM2.06 conditions as in Fig. 6. The LI-1800 used here is slightly different than those that were used at FSEC (see Fig. 5), in particular with a different slit size and passband (4 nm here rather than 6 nm).

From the bulk of many analyses conducted at different sites with several units of the LI-1800 instrument, we found that the relative difference between the modeled irradiance and measured irradiance (direct normal or global tilted) always shows a wavy/wiggled pattern of spectral deviations. Comparing Figs. 5 and 7 shows that the exact shape and amplitude of the pattern may be different from one particular unit to the other. Because of its repetitive nature among a number of carefully calibrated instruments, this pattern cannot be caused by out-of-specification units. It is most probably caused by mechanical or optical limitations in this rugged and portable, still relatively inexpensive, single-monochromator instrument. Fig. 7 and other similar results show that such a pattern does *not* necessarily occur with other types and brands of spectroradiometer. This finding suggests that care is needed when trying to experimentally assess the performance of spectral models, and that the SMARTS model can be used to detect problems or inconsistencies in measured spectra. In any case, the model's per-

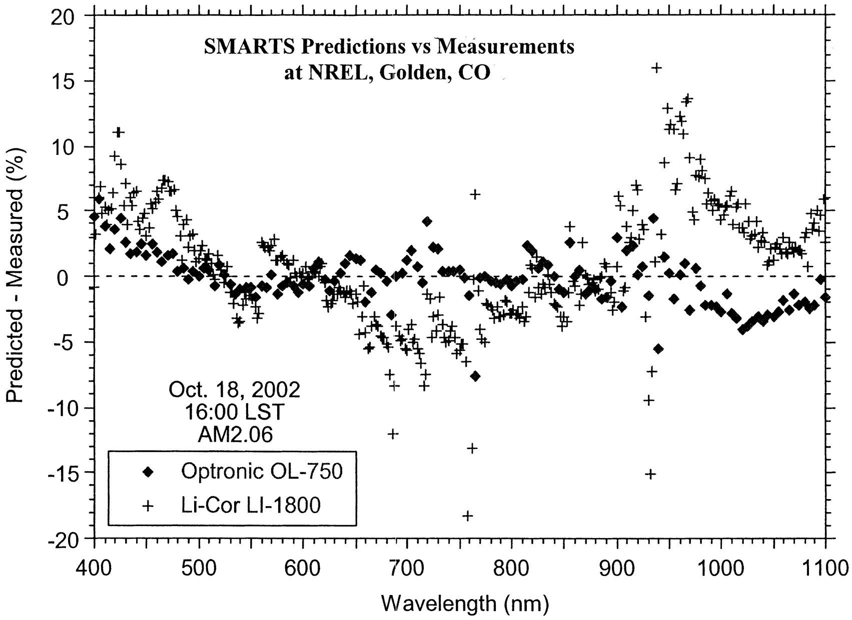

Fig. 7. Percent difference between smoothed SMARTS predictions and measurements from two collocated spectroradiometers for an air mass 2.06. Direct normal irradiance measurements were performed at NREL under clear-sky conditions, 18 October 2002.

formance in the visible and near infrared is well documented, and well adapted to the accuracy requirements of reference spectra.

The model's performance has also been assessed in the UV by multiple comparisons with reference spectroradiometric data. There too, very good agreement has been found over a variety of sun geometries and atmospheric conditions. An example is provided in Fig. 8, where the measured data have been acquired at San Diego, CA with a 2-nm-FWHM double-monochromator Biospherical SUV-100 instrument, as part of the National Science Foundation Polar Program, which monitors UV radiation and ozone at differ-

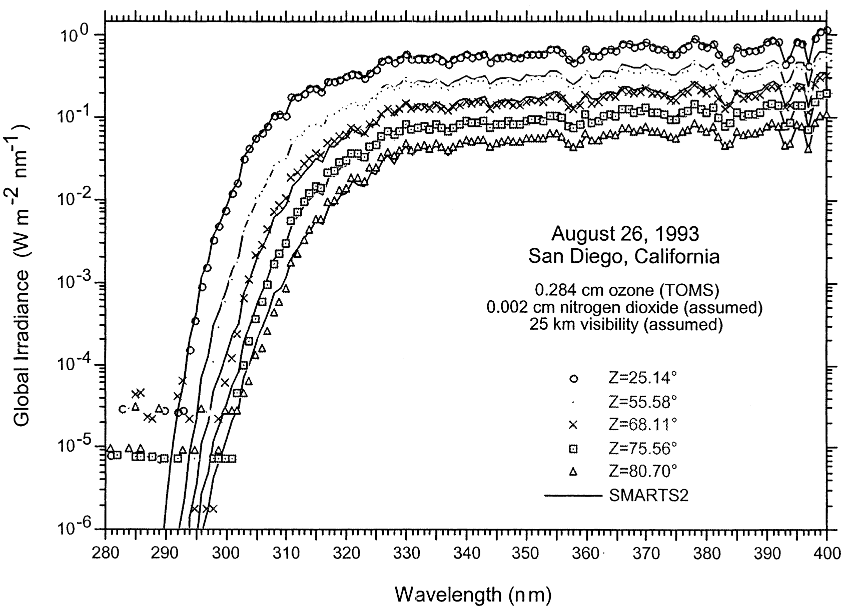

Fig. 8. SMARTS predictions in the UV compared to measured data for a clear day at San Diego, CA.

ent sites (Dahlback, 1996). These instruments undergo elaborate calibration, characterization, and quality-control procedures, and thus provide reliable reference measurements under a variety of atmospheric conditions and zenith angles. These and other results (Gueymard, 1995) show that SMARTS can be used to predict direct and diffuse irradiances in the UV with sufficient resolution and accuracy.

5.3.5. Model flexibility. The SMARTS model is easy to implement and execute; its results compare favorably with high-resolution models, including MODTRAN; and its inputs, outputs, and data libraries offer a large number of user options. For instance, SMARTS allows the user to select from seven extraterrestrial spectra, 10 standard atmosphere profiles, 10 documented aerosol profiles, including a user-generated profile, 36 ground cover materials of differing spectral reflectances, in addition to a user-generated reflectance file, 32 possible output spectral variables, including transmittances and optical thickness for atmospheric constituents, and effective ground reflectances. The effect of aerosol extinction can be specified by a choice of inputs: Ångström coefficients, AOD at 500 nm, meteorological range, or visibility. Receiver geometry is described by user input slope and azimuth angles for the receiving surface, or a 'sun tracking' option.

SMARTS also calculates the circumsolar contribution to simulate receivers with a selectable field-of-view up to 20°-maximum. Five 'default' levels for tropospheric pollution (pristine, standard, light, moderate, severe) due to 10 different absorbers are available. Alternatively, the user can specify volumetric concentrations of any of these 10 absorbers, if desired.

The model has provision for smoothing or degrading the spectral resolution of computed results using either triangular or Gaussian 'filter function' with user-prescribed bandwidth. Thus, model results can be compared with measurement results generated by spectrometers with known spectral passbands, as described in Section 5.3.4 above. All these features make the model an excellent candidate for scientists and engineers wishing to generate both reference standard and other spectra for research purposes.

6. PREVAILING CONDITIONS VERSUS REFERENCE CONDITIONS

6.1. Broadband and meteorological conditions

Table 2 summarizes the irradiance and meteorological conditions stated in *Standard Reporting Conditions* (SRC), or *Standard Test Conditions* (STC) used in the photovoltaic community, and data for the southwestern US from the United States National Solar Radiation Data Base (NREL, 1995) as reported elsewhere (Myers *et al*., 1999, 2000; Kurtz *et al*., 2000).

Table 3 compares SRC and Photovoltaic for Utility Scale Applications (PVUSA) Test Conditions (PTC) with the medians of available

Table 2. Summary of standard conditions

Standard name citation	Irradiance W/m^2	Temperature	Wind speed	Comments
STC or SRC (ASTM, 1998a,b; Emery, 1999; ISO, 1992; IEC, 1989)	1000 Global Global AM1.5 spectrum	25 °C cell (NOCT-ASTM, 1998b)	Not applicable	Indoor peak performance
PVUSA Test Conditions (Whitaker *et al*., 1991)	1000 Global 850 DNI No spectral reference	20 °C ambient	1 m/s at 10 m height	Outdoor peak performance (utilities)
Nominal operating conditions (ASTM, 1998b)	800 Global No spectral reference	20 °C ambient	1 m/s at module height	Nominal operating cell temperature (NOCT-ASTM, 1998b)
'Ad hoc' DNI (Emery *et al*., 2002; Myers *et al*., 2002)	1000 DNI Direct AM1.5 spectrum	20 °C cell	N/A	DNI spectrum scaled by 1.3 for concentrators
Mean prevailing (Myers *et al*., 1999, 2000; Kurtz *et al*., 2000)	1000 Global DNI = 836 ± 44	23.7 ± 8.8 °C ambient	4.5 ± 2.8 m/s at 10 m height	Observed when GNI is 1000 W/m^2

GNI and DNI denote the global normal and direct normal broadband irradiance, respectively, on a two-axis solar-tracking surface (Myers *et al*., 2002).

Table 3. Average medians of prevailing conditions at 1000±10 W/m^2 global normal irradiance for 37 sites in southwest United States compared with 'standard' reporting conditions (Kurtz *et al*., 2000; Myers *et al*., 2000)

Parameter	Average median (prevailing)	S.D.	Standard reporting conditions	PVUSA test conditions
DNI, W/m^2	834.4	22.8	–	850.0
GNI, W/m^2	1001.0	1.3	1000	1000
Ambient temp., °C	24.4	4.0	25[a]	20
Wind speed, m/s	4.4	1.1	–	1.0
Precipitable water, cm	1.4	0.5	1.42	–
Broadband AOD	0.08	0.02	–	–
Spectral AOD at 0.5 μm	–	–	0.27	–
Air mass	1.43	0.09	1.50	–

[a] Device temperature.

meteorological and atmospheric parameters when global normal irradiance (GNI, the global irradiance received on a surface always normal to the sun's direction) approximates an SRC irradiance level of 1 kW/m^2 within ±10 W/m^2. The commonly-used values of 850 W/m^2 for direct normal irradiance (DNI) and 20 °C for ambient temperature appear appropriate for concentrator testing. The water vapor and air mass conditions approximate those defining the ASTM reference spectra. The large difference between the median broadband AOD observed and that used to define the reference direct normal spectra is of importance to the concentrating solar collector community because of the large sensitivity of these spectra to AOD (Myers *et al*., 2002; Emery *et al*., 2002).

Technologies such as multi-junction III–V PV cells are particularly spectrally sensitive. The difference in efficiency due to using the standard *direct* versus *global* spectrum is known to be of the order of 5% for such cells (Emery *et al*., 2002; McMahon *et al*., 2002). Because of the discrepancy between the *prevailing* versus *reference* AOD conditions, we compared available measured spectra to the reference spectra.

6.2. Measured spectra compared with standard spectral distributions

We selected spectra from the SERI Solar Spectral Database (SSDB) developed by Riordan *et al*. (1989) and now available online (http://rredc.nrel.gov/solar) to compare with the current ASTM standard spectra. The SSDB contains over 3300 spectra measured in 1987 and 1988. Spectra were measured with Li-Cor model LI-1800 spectroradiometers located at different sites: FSEC, Cape Canaveral, FL; Pacific Gas and Electric (PG&E), San Ramon, CA; and Denver, CO. Direct-normal measured spectra were selected when the air mass was 1.5±0.1. A total of 144 spectra meeting this criterion were available. (Fig. 5 presents a sample case that has been extracted from this dataset.)

The mean DNI irradiance for the FSEC and PG&E spectra under these conditions were 865±85 W/m^2, and 883±32 W/m^2, respectively. Only four of the 76 Denver direct-normal spectra in the SSDB met the selection criterion, so we randomly selected 500 clear sky spectra from over 3000 spectra collected at the NREL test site (at Golden, near Denver, CO) during PV reference cell calibrations (Osterwald *et al*., 1990). In all, a total of 644 spectra were assembled and analyzed.

As shown in Fig. 9, the means of the observed *direct normal* spectra cluster nearer the global tilt standard spectrum (E892) than to the direct standard spectrum (E891). This is because of the relatively high AOD (0.27) defining the direct reference spectrum, and the significantly lower AOD in the measured dataset. We thus varied the input parameters for the SPCTRAL2 code to make the modeled and mean direct spectra match for each site. Table 4 shows the parameters that accomplish this match.

Because the measured direct spectra cluster near the *global tilted* reference spectrum, we also used SPCTRAL2 (with input parameters also listed in Table 4) to match the global tilted reference spectrum with a modeled *direct-normal* spectrum.

The analysis of prevailing conditions in Table 3 for irradiance values near SRC implies that 850 to 890 W/m^2 are reasonable DNI values for rating concentrator collectors. *Broadband* AOD of ~0.06 to 0.10, obtained by reversing the METSTAT broadband radiation model (Maxwell, 1998), and wind speed of 4 m/s prevail when irradiance conditions are near SRC in the southwest United States. Measured DNI spectra near SRC conditions show the standard direct spectrum is comparatively blue deficient due to the higher AOD used in generating it.

Adjusting the ASTM standard spectra by a

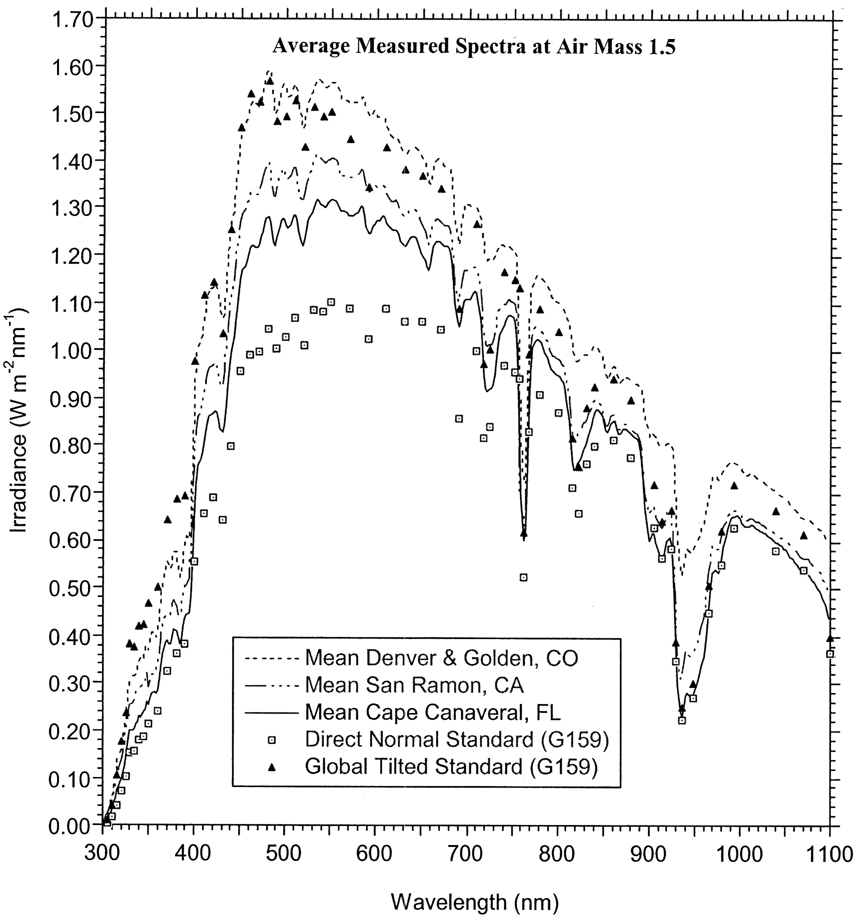

Fig. 9. ASTM direct (squares) and global tilt (triangles) spectra compared with mean measured FSEC (thick line, $N=120$), PG&E (dash-dotted line, $N=20$), and Denver (dashed line, $N=500$) spectra. SPCTRAL2 run with inputs in Table 5 approximate the global reference, and three mean measured spectra.

constant scaling factor to obtain an integrated irradiance of 1 kW/m^2 may lead to values greater than extraterrestrial values in the near infrared. This may distort PV performance results (Bird *et al.*, 1985; Emery, 1999). For the direct normal standard spectrum, which integrates to 768.31 W/m^2, the scale factor to achieve 1 kW/m^2 is 1.30 (=1000/768.31). For the hemispherical tilted standard spectrum, which integrates to 963.75 W/m^2, the correction factor is 1.037 (=1000/963.75). The existing *hemispherical tilt* standard spectrum can also be interpreted as an approxi-

Table 4. SPCTRAL2 inputs for model direct normal spectra that approximate mean measured direct spectra and the ASTM E892 global tilt spectrum with a direct normal spectrum

Inputs	DNI approximating global tilt E892	Match Denver mean	Match FSEC mean	Match PG&E mean
AOD at 0.5 μm	0.05	0.03	0.12	0.08
Angström turbidity exponent[a]	1.14	1.14	1.14	1.14
Albedo	0.2	0.2	0.2	0.2
Ozone, cm	0.28	0.2	0.3	0.3
Zenith angle	22.5	46.21	48.71	47.67
Precipitable water, cm	1.47	0.3	2.0	2.0
Asymmetry factor[a]	0.65	0.65	0.65	0.65
Angle of incidence	0	0	0	0
Surface slope	22.5	46.21	48.71	47.67
Pressure, mb	1013	840	1013	990
Day of year	120	120	90	90
Air mass	1.08	1.44	1.52	1.48

[a] Model defaults.

mate *direct-normal* spectrum under specific conditions. However, from a scientific standpoint, the development of specific hemispherical tilted and direct normal for 'standard' conditions is preferable to these simplistic adjustments.

6.3. Selecting atmospheric properties

A large number of direct and global spectra recorded at different US sites have been analyzed to (i) validate the SMARTS radiative code under a variety of real atmospheric and environmental conditions; and (ii) define the appropriate atmospheric conditions under which PV power production is maximized, and weathering and durability conditions are near optimum (Emery *et al.*, 2002). The criterion chosen was to select sites in the NSRDB with at least 6 kWh/m^2 yearly-average direct normal daily irradiation. Table 5 lists the 15 sites meeting this criterion.

The mean AOD at 500 nm for these sites is 0.085, from an analysis performed with version 2.8 of SMARTS. The same analysis if performed with its latest version (2.9.2) would yield an AOD closer to 0.084, due to the changes that occurred between versions 2.8 and 2.9. *We propose that the new revised spectra be based on the same atmospheric conditions specified for the present standards, except the AOD at* 500 *nm be specified as* 0.084. This combination is suggested since in conjunction with a specific realistic spectral albedo file (included with the SMARTS model) for 'light soil'—rather than the artificial uniform albedo of 0.2 used in the current standard—the integrated values of the hemispherical tilted spectrum is 1000.37 W/m^2, or essentially the 1000 W/m^2 representing SRC for flat plate PV testing. The integral for the direct normal spectrum for these conditions is 900.17 W/m^2, or essentially 900 W/m^2. Fig. 10 compares the resulting proposed spectra with the existing standard spectra. Because of the considerable decrease of AOD (from 0.27 to 0.084) between the existing standard spectra and the proposed reference spectra, the circumsolar contribution to the direct normal spectrum is also substantially reduced. It drops from 1.4% to 0.5% at 450 nm, and from 0.73% to 0.25% on average over the whole spectrum.

We argue that the revised spectra are more realistic and are representative of more appropriate conditions for the intended applications. The average percentage of reading difference between the proposed tilted hemispherical spectrum and the historical hemispherical standard spectrum is less than 0.01 W/m^2/nm (or 4%, the measurement uncertainty in a modern high quality spectroradiometer) for most data in the region from 305 to 1100 nm, reducing the impact of the proposed change on the crystalline silicon flat plate PV community.

7. RECOMMENDATIONS

The existing E892 or G159-98 global hemispherical reference spectrum for a south-facing 37°-tilted surface has served well to meet the needs of the flat plate photovoltaic research, development, and industrial community. The discussion of measurements of prevailing conditions versus reference spectra shows that this hemispherical reference spectrum can be attained under a variety of conditions, and these conditions can be interpreted as representative for many combinations of atmospheric parameters (Riordan and Hulstrom, 1990). The global hemispherical refer-

Table 5. NSRDB site data for sites with annual daily mean DNI of at least 6 kWh/m^2 (Emery *et al.*, 2002; Myers *et al.*, 2002)

Station	Direct beam kWh/m^2	AOD at 500 nm	Broadband AOD
Daggett, CA	7.50	0.087	0.058
Las Vegas, NV	7.10	0.105	0.068
Tucson, AZ	7.00	0.099	0.065
Phoenix, AZ	6.80	0.142	0.090
Prescott, AZ	6.80	0.074	0.050
Alamosa, CO	6.80	0.029	0.024
Albuquerque, NM	6.70	0.074	0.050
Tonopah, NV	6.70	0.082	0.055
El Paso, TX	6.70	0.118	0.076
Flagstaff, AZ	6.40	0.074	0.050
Reno, NV	6.20	0.091	0.060
Cedar City, UT	6.20	0.074	0.050
Pueblo, CO	6.10	0.074	0.050
Tucumcari, NM	6.10	0.099	0.065
Ely, NV	6.00	0.050	0.036
Regional average	⟨6.61⟩	⟨0.085⟩	⟨0.056⟩

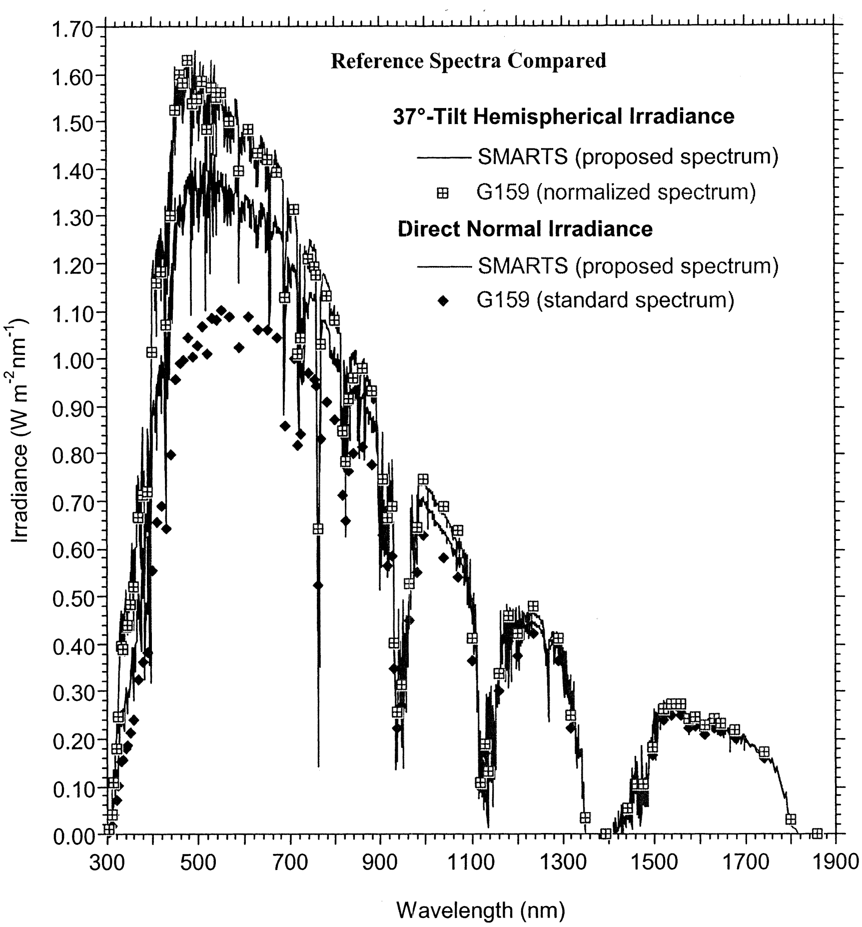

Fig. 10. Proposed vs. existing AM1.5 spectra: proposed reference hemispherical (top line, 1000.37 W/m^2) vs. ASTM G159 hemispherical (normalized to 1000 W/m^2; crossed squares), for 37° sun-facing tilted surface; proposed reference direct normal (bottom line) vs. ASTM G159 direct normal (diamonds).

ence spectra has become ingrained in the flat-plate PV community to such an extent that major modifications would have far-reaching implications on the economy of the industry.

Therefore, we recommend correction of minor problems with the existing hemispherical tilted reference, and various improvements, such as the ability to generate the spectrum from existing documentation, uniform spectral interval, and more data in the ultraviolet. Many different combinations of atmospheric conditions produce spectra that closely match or approximate the global reference spectrum, complicating the definition of an 'appropriate' direct normal spectrum.

The PV community addressing the technology of concentrating solar collectors desires a direct normal spectrum representing conditions where PV power production is most likely to develop, such as the sites analyzed in Table 5. These same sites are also representative of the climate characteristics needed for testing the weathering and durability of materials, i.e. high solar irradiance and few cloudy days.

The 'historical' hemispherical standard spectra should be approximated with the new generating model as closely as possible to provide a link between past, current, and future work with respect to spectral weighting applications. The current global spectral standard includes the 'scaled' global spectrum to produce an integrated value of 1000 W/m^2, which has been considered, anecdotally, as a reasonable, achievable, round number for relative performance evaluations under clear-sky conditions near solar noon. The scaled, or normalized hemispherical spectrum was obtained by multiplying the standard spectrum by a fixed value of 1.037. Using SMARTS rather than this simplistic procedure, we easily produce a hemispherical tilt spectrum with an integrated irradiance value of 1000 W/m^2, which is actually more representative of typical atmospheric and ground albedo conditions meeting the needs of the

PV and weathering and durability community. The new hemispherical spectrum will be available to fill the role of the older 'scaled' historical spectrum. There would be no need for artificial scaling of the spectral data to match photovoltaic Standard Reporting Condition total irradiance conditions. The spectral 'mismatch error' (Emery and Osterwald, 1988; Emery *et al*., 2002; Seaman, 1982) due to using the old 'historical' and new (or any other) spectra can be explicitly calculated.

The corresponding direct normal spectral integral for the conditions selected is 900 W/m^2. Though 50 W/m^2 higher than the 850 W/m^2 for PVUSA test conditions, this is only a 5% difference with respect to the prevailing conditions discussed in Section 6.1. Table 6 lists the input parameters generating the proposed revised spectral distributions, which are shown in Fig. 10. Note the use of realistic spectral albedo data (Fig. 11) representing characteristics of a light sandy soil. This albedo has been adapted from measured data in the ASTER library (Hook, 1998). Furthermore, typical directional reflectance properties for natural surfaces are considered here. These realistic reflectance conditions replace the ideally constant and Lambertian 0.2 albedo used for the existing reference spectra.

We recommend that the basis of these revised spectral standards be the SMARTS model, and that the model and supporting data files and documentation be provided as adjunct material to the reference standards. This would allow the user to not only generate the reference spectra 'at will', but also all of the constituent radiometric components of the relevant spectrum, such as the diffuse spectral irradiance, circumsolar irradiance, or reflected irradiance.

The same model can also be used to generate 'test' spectra to compare with measured spectra at various resolutions (as discussed in Section 5.3), and for theoretical studies of the impact of spectral variations on spectrally selective devices—all with exactly the same basis as the reference spectra.

8. CONCLUSIONS

Existing tabulated terrestrial reference spectral distributions of sunlight were developed in the early 1980s, and have not been updated except for editorial changes. In fact, these spectra cannot be explicitly regenerated, corrected or transparently modified, as the generating tools are no longer available. To meet the needs of the scientific and engineering communities utilizing these standards, improved reference spectra, and documentation of the means to produce them are needed. Fortunately, there have been significant improvements in our knowledge of atmospheric constituents and their properties, as well as radiative transfer models.

Of particular importance is the finding that the aerosol optical depth originally chosen for the existing standard spectra (0.27 at 500 nm) does not appear representative of the very conditions where these spectra are needed most. Reference

Table 6. SMARTS inputs to produce approximations of current and proposed reference spectra

Inputs	Previous E891/E892/G159 'historical best match'	New proposed reference spectra
Sun's zenith angle (°)	48.236	48.236
Air mass	1.50	1.50
Surface slope/azimuth (°)	37/180	37/180
Angle of incidence, beam normal/hemispherical tilt (°)	0/11.236	0/11.236
Field-of-view, total angle, beam normal/hemispherical tilt (°)	5.8/N/A	5.8/N/A
Extraterrestrial spectrum	MODTRAN/Wehrli	SMARTS/Gueymard
Earth–sun distance correction	1	1
Model atmosphere	USSA[a]	USSA[a]
Aerosol model	S&F Rural[b]	S&F Rural[b]
Surface pressure[a] (mb)	1013.25	1013.25
AOD at 0.5 μm	0.270	0.084
Carbon dioxide mixing ratio	330 ppm[a]	370 ppm
Pollution level	Standard	Standard
Ozone[a] (atm-cm)	0.344	0.344
Precipitable water[a] (cm)	1.416	1.416
Albedo	0.2, Lambertian	Light sandy soil, non-Lambertian

N/A, not applicable.
[a] USSA, US standard atmosphere.
[b] Shettle and Fenn rural aerosol profile (Shettle and Fenn, 1979).

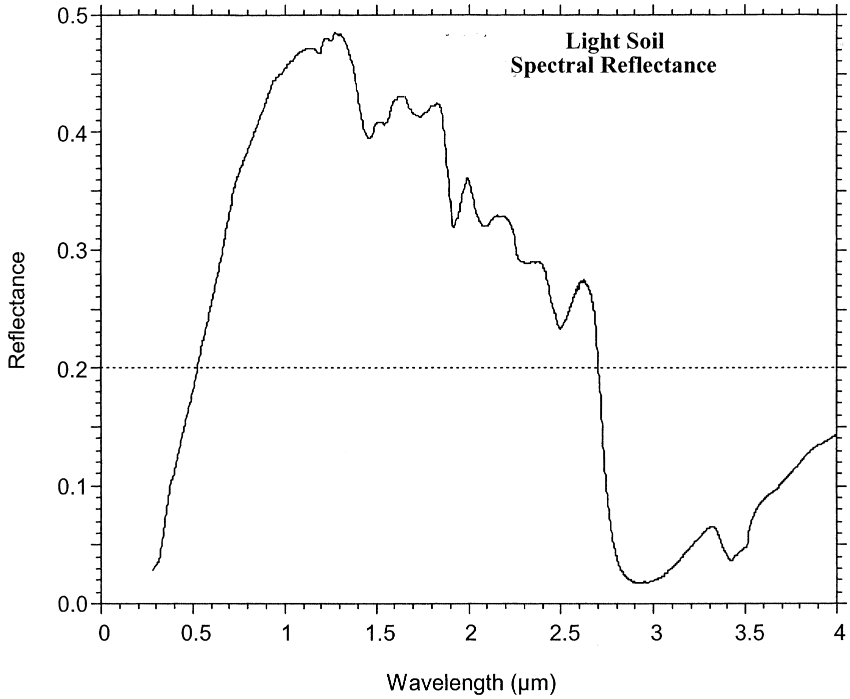

Fig. 11. Plot of 'light sandy soil' albedo file used for reference spectral distribution, as derived from Jet Propulsion Laboratory ASTER spectral reflectance library. Albedo in the current G159 standard spectra is represented by the horizontal dashed line.

atmospheric conditions, i.e. those needed to develop reference spectra representative of important weathering and solar energy producing climates, have been successfully quantified. The atmospheric conditions selected (in particular, AOD = 0.084 at 500 nm) result in only limited change to the currently widely used hemispherical tilted reference spectrum. Conversely, the direct spectrum is very sensitive to the aerosol load of the atmosphere. The new reference spectrum proposed here has a more realistic, increased amplitude in the visible and near-infrared regions, which might maximize the use of concentrators that utilize only the direct component.

The SMARTS spectral model has been shown to be highly accurate (with predicting performance comparable to complex models such as MODTRAN) and easy to implement and run. Its accuracy is compatible with most scientific applications, and more than sufficient for engineering use. Documentation of the model is extensive. By establishing both the revised reference spectra, and the model to re-generate them at any time, scientists and engineers will be given improved tools to assess the impact of terrestrial spectral variations on their technology of interest. We propose SMARTS be used to generate reference spectra for global tilted surfaces, direct normal applications, and ultraviolet applications. Use of this model can provide various benefits: (1) historical continuity and linkage to the existing standards, (2) spectra representative of realistic conditions, (3) spectra representative of maximal or extreme, yet still reasonable, conditions, and finally (4) a means of evaluating atmospheric conditions by comparing model results with measured data.

The SMARTS code, related data files, and reference spectra proposed here can be obtained at http://rredc.nrel.gov/sdar/models/SMARTS.

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REFERENCES

American Meteorological Society (1980). In 3rd printing, Glossary of Meteorology, p. 597.

Anderson G. P., Chetwynd J. H., Theriault J. M., Acharya P., Berk A., Robertson D. C., Kneizys F. X., Hoke M. L., Abreu L. W. and Shettle E. P. (1993) MODTRAN2: suitability for remote sensing. In Proceedings of the Conference on Atmospheric Propagation and Remote Sensing, Vol. 1968, pp. 514–525, Society of Photo-Optical Instrumentation Engineers.

Anderson G. P. et al. (1994) History of one family of atmospheric radiative transfer codes. In Passive Infrared Remote Sensing of Clouds and the Atmosphere, Vol. II, Society of Photo-optical Instrumentation Engineers.

Anderson G. P. et al. (1996) Reviewing atmospheric radiative transfer modeling: new developments in high and moderate resolution FASCODE/FASE and MODTRAN. In Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research, Vol. II, Society of Photo-Optical Instrumentation Engineers.

Ångström A. (1929) On the atmospheric transmission of sun radiation and on dust in the air. *Geografis Ann.* **2**, 156–166.

Anon (1976). *US Standard Atmosphere, 1976*, NOAA/NASA/USAF, Washington, DC, Online version at http://nssdc.gsfc.nasa.gov/space/model/atmos/us_standard.html.

ASTM (1973). *Extraterrestrial Spectral Solar Irradiance Distribution, Standard E490-73*, American Society for Testing and Materials, Philadelphia, PA.

ASTM (1987a). *Standard Tables for Terrestrial Direct Normal Solar Spectral Irradiance for Air Mass 1.5, Standard E891*, American Society for Testing and Materials, Philadelphia, PA.

ASTM (1987b). *Standard Tables for Terrestrial Solar Spectral Irradiance at Air Mass 1.5 for a 37° Tilted Surface, Standard E892*, American Society for Testing and Materials, Philadelphia, PA.

ASTM (1998a). *Standard Tables for Reference Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37° Tilted Surface, Standard G159-98*, American Society for Testing and Materials, West Conshohocken, PA.

ASTM (1998b). *Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells, Standard E1036*, American Society for Testing and Materials, West Conshohocken, PA.

ASTM (2000). *Standard Solar Constant and Air Mass Zero Solar Spectral Irradiance Tables, Standard E490-00*, American Society for Testing and Materials, West Conshohocken, PA.

Berk A., Bernstein L. S. and Robertson D. C. (1989). *MODTRAN: A Moderate Resolution Model for LOWTRAN 7, Rep. GL-TR-890122*, Geophysics Directorate, Phillips Laboratory, Hanscom AFB, MA 01731.

Berk A. et al. (1999) MODTRAN4 radiative transfer modeling for atmospheric correction. In SPIE Proceedings, Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research III, Vol. 3756, Society for Photo-Optical Instrumentation Engineers.

Bird R. and Hulstrom R. (1979). *Application of Monte Carlo Techniques to Insolation Characterization and Prediction, Report SERI-RR-36-306*, SERI, Golden, CO.

Bird R. E. (1982) Terrestrial solar spectral modeling. *Solar Cells* **7**, 107–118.

Bird R. E. (1984) A simple, solar spectral model for direct-normal and diffuse horizontal irradiance. *Solar Energy* **32**, 461–471.

Bird R., Hulstrom R. and Riordan C. (1985) Normalization of direct beam spectral irradiance data for photovoltaic cell performance analysis. *Solar Cells* **14**, 193–195.

Bird R. E. and Hulstrom R. L. (1983) Additional solar spectral data sets. *Solar Cells* **8**, 85–95.

Bird R. E. and Riordan C. (1986) Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the Earth's surface for cloudless atmospheres. *J. Clim. Appl. Meteorol.* **25**, 87–97.

Bird R. E., Hulstrom R. L. and Lewis L. J. (1983) Terrestrial solar spectral data sets. *Solar Energy* **30**, 563–573.

Blättner W. (1983). *Utilization Instruction for the BRITE Monte-Carlo Procedure, Research Note RRA-N8303*, Radiation Research Associates, Fort Worth, TX.

Blumenthaler M. (1993) Solar UV measurements. In *UV-B Radiation and Ozone Depletion, Effects on Humans, Animals, Plants, Microorganisms, and Materials*, Tevini M. (Ed.), CRC Press, Boca Raton, FL.

Braslau N. and Dave J. V. (1973) Effect of aerosols on the transfer of solar energy through realistic model atmospheres. *J. Appl. Meteorol.* **12**, 601–619.

Brine D. T. and Iqbal M. (1983) Diffuse and global solar spectral irradiance under cloudless skies. *Solar Energy* **30**, 447–453.

Brueckner G. E., Edlow K. L., Floyd L. E., Lean J. L. and VanHoosier M. E. (1993) The solar ultraviolet spectral irradiance monitor (SUSIM) experiment on board the upper atmosphere research satellite (UARS). *J. Geophys. Res.* **98D**, 10695–10711.

Clough S. A. et al. (1981). *Atmospheric Spectral Transmittance and Radiance: FASCOD1B*, Society of Photo-Optical Instrumentation Engineers, Washington, DC.

Collins D. G., Blättner W. G., Wells M. B. and Horak H. G. (1972) Backward Monte Carlo calculations of polarization characteristics of the radiation emerging from spherical-shell atmospheres. *Appl. Opt.* **11**, 2684–2696.

Dahlback A. (1996) Measurements of biologically effective UV doses, total ozone abundances, and cloud effects with multichannel, moderate bandwidth filter instruments. *Appl. Opt.* **35**, 6514–6521.

Elterman L. (1968). *UV, Visible, and IR Attenuation for Altitudes to 50 km, 1968. Report AFCRL-68-0153*, Air Force Cambridge Research Lab., USAF, Hanscom, MA.

Emery K. and Osterwald C. R. (1988) Efficiency measurements and other performance-rating methods. In Current Topics in Photovoltaics, Vol. 3, pp. 301–350, Academic Press.

Emery K., Myers D. and Kurtz S. (2002) What is the appropriate reference spectrum for characterizing concentrator cells? In *Proceedings 29th IEEE Photovoltaic Specialists Conference*, New Orleans, LA, May 20–24, IEEE, New York.

Emery K. (1999) The rating of photovoltaic performance. *IEEE Trans. Electron Dev.* **46**, 1928–1931.

Gonzalez C. C. and Ross R. G. (1980) Performance measurement reference conditions for terrestrial photovoltaics. In *Proceedings of the International Solar Energy Society Conference*, Phoenix, AZ.

Gueymard C. (1993) Development and performance assessment of a clear sky spectral radiation model. In *Proceedings Solar '93—22nd ASES Conference*, pp. 433–438, American Solar Energy Society, Washington, DC.

Gueymard C. (1994) Updated transmittance functions for use in fast spectral direct beam irradiance models. In *Proceedings Solar 94 Conference*, pp. 355–360, ASES, San Jose, CA.

Gueymard C. (1995). In *SMARTS2, Simple Model of the Atmospheric Radiative Transfer of Sunshine: Algorithms and Performance Assessment, Report FSEC-PF-270-95*, Florida Solar Energy Center, Cocoa, FL.

Gueymard C. (2001b) Spectral models. In *Solar Energy—The State of the Art*, Gordon J. (Ed.), pp. 527–531, James and James, London.

Gueymard C. (2002). *SMARTS Code, Version 2.9.2 User's Manual*, Solar Consulting Services, PDF document available online, http://rredc.nrel.gov/solar/models/SMARTS.

Gueymard C. (1998) Turbidity determination from broadband irradiance measurements: a detailed multicoefficient approach. *J. Appl. Meteorol.* **37**, 414–435.

Gueymard C. (2001) Parameterized transmittance model for direct beam and circumsolar spectral irradiance. *Solar Energy* **71**, 325–346.

Hook S. J. (1998). *ASTER Spectral Library*, Jet Propulsion Laboratory, http://speclib.jpl.nasa.gov.

Hulstrom R., Bird R. and Riordan C. (1985) Spectral solar irradiance data sets for selected terrestrial conditions. *Solar Cells* **15**, 365–391.

IEC (1989). *Photovoltaic Devices: Part 3. Measurement Principles for Terrestrial Photovoltaic (PV) Solar Devices with Reference Spectral Irradiance Data. Standard IEC 904-3*, International Electro Technical Commission.

ISO (1992). *Solar Energy—Reference Solar Spectral Irradiance at the Ground at Different Receiving Conditions, Pt. 1. Standard 9845-1*, International Organization for Standardization, Geneva.

Justus C. G. and Paris M. V. (1985) A model for solar spectral irradiance and radiance at the bottom and top of a cloudless atmosphere. *J. Clim. Appl. Meteorol.* **24**, 193–205.

Kneizys F. X., Shettle E. P., Gallery W. O., Chetwynd J. H., Abreu L. W., Selby J. A., Fenn R. W. and McClatchey R. A. (1980). *Atmospheric Transmittance/radiance, Computer Code LOWTRAN 5. Report AFGL TR-80-0067*, Air Force Geophysics Lab., Hanscom AFB, MA.

Kneizys F. X., Shettle E. P., Abreu L. W. and Chetwynd J. H. (1988). *Users Guide to LOWTRAN 7. Report AFGL TR-88-0177*, Air Force Geophysics Lab., Hanscom AFB, MA.

Konratyev K. Y. (1969). *Radiation in the Atmosphere*, Academic Press, New York.

Koschmieder H. (1924) Theorie der horizontalen Sichtweite. *Beitr. Phys. Atmos.* **12**, 33–53.

Kurtz S., Myers D., Townsend T., Whitaker C., Maish A., Hulstrom R. and Emery K. (2000) Outdoor rating conditions for photovoltaic modules and systems. *Solar Energy Mater. Solar Cells* **62**, 379–391.

Kurucz R. L. (1995) The solar irradiance by computation. In *Proceeedings 17th Annual Review Conference on Atmospheric Transmission Models. PL/TR-95-2060*, USAF Phillips Lab, Hanscom, MA.

Leckner B. (1978) The spectral distribution of solar radiation at the Earth's surface—elements of a model. *Solar Energy* **20**, 143–150.

Linke F. (1922) Transmission Koefficient und Trübungsfaktor. *Beitr. Phys. Frei Atmos.* **10**, 91–103.

Matthews L. K., Mulholland G. P. and Stevens M. (1987) Measurement and analysis of solar spectral irradiance. In *Proceedings ASME/JSME/JSES Solar Engineering Conference*, Honolulu, HI, pp. 307–313.

Maxwell E. L. (1998) METSTAT—The solar radiation model used in the production of the National Solar Radiation Data Base (NSRDB). *Solar Energy* **62**, 263–279.

McClatchey R. A. (1979) Atmospheric transmission models and measurements. In *Proceedings Atmospheric Effects on Radiative Transfer Seminar*, Society of Photo-optical Instrumentation Engineers.

McMahon W. E., Kurtz S., Emery K. and Young M. S. (2002) Criteria for the design of GaInP/GaAs/Ge triple-junction cells to optimize performance outdoors. In *Proceedings 29th IEEE Photovoltaic Specialists Conference*, New Orleans, LA, May 20–24, IEEE, New York.

Mecherikunnel A. T. and Richmond J. C. (1980). *Spectral Distribution of Solar Radiation. NASA Tech. Mem. 82021*, Goddard Space Flight Center, Greenbelt, MD.

Molineaux B., Ineichen P. and O'Neill N. (1998) Equivalence of pyrheliometric and monochromatic aerosol optical depths at a single key wavelength. *Appl. Opt.* **37**, 7008–7018.

Moon P. (1940) Proposed standard solar radiation curves for engineering use. *J. Franklin Inst.* **230**, 583–617.

Myers D., Kurtz S., Whitaker C., Townsend T. and Maish A. (1999) Objective method for selecting outdoor reporting conditions for photovoltaic performance. In *Proceedings Solar '99*, pp. 267–272, American Solar Energy Society, Boulder, CO.

Myers D. R., Kurtz S. R., Emery K., Whitaker C. and Townsend T. (2000) Outdoor meteorological broadband and spectral conditions for evaluating photovoltaic modules. In *Proceedings 28th Photovoltaic Specialists Conference*, Anchorage, AK, IEEE.

Myers D. R., Emery K. and Gueymard C. (2002) Proposed reference spectral irradiance standards to improve photovoltaic concentrating system design and performance evaluation. In *Proceedings 29th Photovoltaic Specialists Conference*, New Orleans, LA, May 20–24, IEEE, New York.

Myers D. R. (1989) Estimates of uncertainty for measured spectra in the SERI spectral solar radiation data base. *Solar Energy* **43**, 347–353.

Nann S. and Riordan C. (1991) Solar spectral irradiance under clear and cloudy skies: measurements and a semiempirical model. *J. Appl. Meteorol.* **30**, 447–462.

Neckel H. and Labs D. (1981) Improved data of solar spectral irradiance from 0.33 to 1.25 μm. *Solar Phys.* **74**, 231–249.

NREL (1995). *National Solar Radiation Data Base (1961–1990). Final Technical Report, NREL TP-463-5784*, National Renewable Energy Laboratory, Golden, CO.

Osterwald C. R. (1992) Photovoltaic standards development within ASTM. In Photovoltaic Advanced Research and Development Projects, Proceedings 11th Review Meeting Conference, Vol. 268, AIP, New York.

Osterwald C. R., Emery K., Myers D. R. and Hart R. E. (1990) Primary reference cell calibrations at SERI: history and methods. In *Proceedings 21st Photovoltaic Specialists Conference*, Kissimmee, IEEE, pp. 1062–1067.

Riordan C. (1987). *Extraterrestrial Spectral Solar Irradiance Data for Modeling Spectral Solar Irradiance at the Earth's Surface. Report SERI TR-215-2921*, Solar Energy Research Institute, Golden CO.

Riordan C. (1990). *SPCTRAL2, FORTRAN computer program*, NREL, Golden, CO.

Riordan C. and Hulstrom R. (1990) What is an air mass 1.5 spectrum? In *Proceedings 21st IEEE PV Specialists Conference*, Institute of Electrical and Electronic Engineers.

Riordan C., Myers D., Rymes M., Hulstrom R., Marion W., Jennings C. and Whitaker C. (1989) Spectral solar radiation data base at SERI. *Solar Energy* **42**, 67–79.

Rothman L. S. (1978) Update of the AFGL atmospheric absorption line parameters compilation. *Appl. Opt.* **17**, 3517–3518.

Rothman L. S. et al. (1992) The HITRAN molecular database: editions of 1991 and 1992. *J. Quant. Spectrosc. Radiat. Transfer* **48**, 469–507.

Rothman L. S. et al. (1998) The HITRAN molecular spectroscopic database and HAWKS (HITRAN Atmospheric WorkStation): 1996 edition. *J. Quant. Spectrosc. Radiat. Transfer* **60**, 665–710.

Seaman C. H. (1982) Calibration of solar cells by the reference cell method—the spectral mismatch problem. *Solar Energy* **29**, 291–298.

Shettle, E. P. (1989) Models of aerosols, clouds and precipitation for atmospheric propagation studies. In *Conference on Atmospheric Propagation in the UV, Visible, IR and mm-Wave Region and Related Systems Aspects*, Copenhagen, Denmark, AGARD, Vol. 454, 15.1–15.13.

Shettle, E. P. and Fenn R. W. (1975) Models of the atmospheric aerosol and their optical properties. In *AGARD Conference No. 183: Optical Propagation in the Atmosphere; Electronic Wave Propagation Panel Symposium*, Lyngby, Denmark, 2.1–2.16.

Shettle E. P. and Fenn R. W. (1979). *Models for the Aerosols of the Lower Atmosphere and the Effects of Humidity Variations on their Optical Properties, Report AFGL-TR-79-014*, Air Force Geophysics Lab, Hanscom, MA.

Thekaekara M. P. (1974) Extraterrestrial solar spectrum. *Appl. Opt.* **13**, 518–522.

Thuillier G., Hersé M., Simon P. C., Labs D., Mandel H., Gillotay D. and Foujols T. (1998) The visible solar spectral irradiance from 350 to 850 nm as measured by the SOLSPEC spectrometer during the ATLAS1 mission. *Solar Phys.* **177**, 41–61.

Utrillas M. P., Bosca J. V., Martinez-Lozano J. A., Cañada J., Tena F. and Pinazzo J. M. (1998) Comparative study of SPCTRAL2 and SMARTS2 parameterized models based on spectral irradiance measurements at Valencia (Spain). *Solar Energy* **63**, 161–172.

Walker J. H. et al. (1987). *Spectral Irradiance Calibrations. NBS Special Publication 250-20*, National Institute of Standards and Technology, Gaithersburg, MD.

Wang J. and Anderson G. P. (1994) Validation of FASCOD3 and MODTRAN3: comparison of model calculations with interferometer observations from SPECTRE and ITRA. In Passive Infrared Remote Sensing of Clouds and the Atmosphere II, Vol. 2309, Society of Photo-Optical Instrument Engineers (SPIE).

Whitaker C., Townsend T. U., Newmiller J. D., King D. L., Boyson W. E., Kratochvil J. A., Collier D. E. and Osborn D. E. (1991) Effects of irradiance and other factors on PV temperature coefficients. In *Proceedings 22nd PV Specialists Conference*, Las Vegas, NV, Institute of Electrical and Electronics Engineers, pp. 1253–1256.